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K. J. Plotkin, J. E. Robertson, and J. A. Cockburn

Wyle Laboratories

Eastern Operations, Huntsville, Alabama

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ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
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NOTICES

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FOREWORD

The study reported herein was sponsored by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC) under Program Element 65802F. Air Force Project Manager for this study was Mr. Charles V. Bennett, AEDC/DEL.

The study was conducted by the Wyle Laboratories, Eastern Operations, Huntsville, Alabama, under Contract F40600-72-C-0007 during the period from March 13, 1972 to June 30, 1972.

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This technical report has been reviewed and is approved.

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Project Officer	Lt Colonel, USAF
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ABSTRACT

A study to evaluate the environmental impact of the noise produced by a proposed High Reynolds Number Tunnel (HIRT) under consideration at the Arnold Engineering Development Center (AEDC) has been conducted by Wyle Laboratories. During earlier studies, the noise characteristics of the HIRT facility were defined. These studies included 1) theoretical analyses of the noise generation mechanisms associated with the operation of the facility, and 2) scale-model experiments to provide base-line data for extrapolation to full-scale conditions. The assessment of environmental impact, based on the predicted noise environment of the full-scale facility, is the subject of this report. This assessment contains all pertinent data of relevance to the noise impact which may be anticipated during HIRT operation and includes 1) a summary of the Noise Characteristics of HIRT, 2) Specification of Acceptable Noise Limits for people, animals and buildings which will be exposed to HIRT noise, 3) the Environmental Impact of HIRT noise as evaluated by comparing HIRT noise with acceptable limit criteria, and 4) Special Considerations for Noise Protection and Control. The assessment presented herein indicates that HIRT noise will be within acceptable limits for people residing in the most heavily populated areas of surrounding communities. However, it was found that there are several areas where the anticipated noise levels are sufficiently close to permissible levels to warrant close monitoring during facility shakedown tests to assure that excessive annoyance is not imposed. These are the hospital located in Manchester, Tennessee and the Interstate Highway (I-24) which passes through the AEDC reservation. In addition, there are a few isolated rural houses near the reservation boundary which may experience noise levels slightly above recommended nighttime limits. If it is determined by facility shakedown noise monitoring that acceptable noise levels will be exceeded in these limited areas, it can be avoided by means of proper scheduling of the facility usage. On the AEDC complex, the noise levels within 3,000 feet of HIRT exceed that allowable for unprotected outdoor workers and must therefore be a controlled access area during HIRT operation. Within the developed AEDC complex, various control zones and warning systems are proposed for protection of AEDC personnel from extreme noise environments. The impact of HIRT noise on wildlife in the area is sufficiently small to be discarded as a potential problem area. No damage to AEDC buildings is anticipated; however, one large window in the model shop will be exposed to overpressures approaching that necessary to break single strength glass and therefore may require the utilization of double strength glass.*

*Subsequent to the preparation of this report, it was determined that the subject window is already equipped with double strength glass.

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1.0 INTRODUCTION

A study to evaluate the environmental impact of the noise produced by a proposed High Reynolds Number Tunnel (HIRT) under consideration at the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC) (see Reference 1) has been conducted by Wyle Laboratories. The work reported herein was sponsored by AEDC under Contract No. F40600-72-C-0007 during the period from March 13, 1972 through June 30, 1972.

The HIRT facility is an open circuit, blowdown type Ludwieg-tube wind tunnel which will exhaust into the atmosphere up to 165,000 pounds of air for each second of operation. The rapid onset of the exhaust mass flux in a time of 50 milliseconds or less, and the continuous operation at a high mass flow rate for a period of approximately three seconds will result in a significant noise environment. During the starting process, the rapid increase in mass flux will produce a starting shock wave resembling a blast wave or sonic boom. Immediately following the starting process, the exhaust flow with constant mass flux will produce steady shear-flow noise resembling that of high-speed jet exhaust noise. Early in the design stage of the HIRT facility, these two noise mechanisms were recognized as potentially hazardous noise sources. Consequently, effort was made through exhaust system design to minimize the noise associated with the operation of the facility. However, because of the large size of the facility, its unique and complex design, and the enormous amount of energy which it will release into the atmosphere, a detailed experimental and theoretical study was required to define the noise produced and to assess its impact on the environment.

An extensive study has been performed by Wyle Laboratories to provide a detailed analysis of the HIRT noise environment. This study has consisted of both theoretical predictions and scale model experiments as described below:

1) Predictions of the HIRT noise environment for both the starting transient and steady state operation have been performed based on acoustic models of the noise generating mechanisms associated with the facility operation. The results of the theoretical predictions are presented in Reference 2. Also, refined estimates have been made for the HIRT starting process and the results of this study are presented herein as Appendix A.

2) Measurement of the shear-flow noise generated during steady-state operation of the facility have been obtained through tests of a 1/13 scale model of HIRT. Prediction of the full-scale noise environment was made based on scaling the model test results to full-scale conditions. This program was conducted in coordination with AEDC-VKF personnel and the results are presented in Reference 3.

The results of the studies described above indicate that the noise produced by the HIRT facility is indeed an important factor to be considered in the assessment of Environmental Impact. An analysis of the projected environmental consequences of HIRT noise during operation of the facility is presented in this report.

A brief description of the full-scale HIRT facility is presented in Section 2.0. Section 3.0 contains a brief discussion of the noise characteristics of HIRT, unweighted by subjective response, as determined through previous theoretical and experimental studies described in (1) and (2) above. Section 4.0 presents a discussion of Noise Rating Scales and the Specification of Noise Limits based on the results of related studies by other investigators. Section 5.0 presents an assessment of the environmental impact of HIRT noise based on a comparison of subjectively weighted noise levels with acceptable noise limits. Section 6.0 presents a summary of various methods of noise protection and control which may be implemented to reduce the environmental impact of the noise. Finally, Section 7.0 presents a summary of the conclusions resulting from this study.

2.0 DESCRIPTION OF HIRT

The High Reynolds Number Tunnel, hereafter referred to by the acronym HIRT, is a high pressure, low temperature blowdown wind tunnel which incorporates the Ludwieg tube concept in its operations. Specification of the preliminary design concept and performance evaluation of this facility was performed by the von Karman Facility (VKF) at the Arnold Engineering Development Center (AEDC), Arnold Air Force Station, Tennessee. A comprehensive description of the proposed facility and a comparative evaluation of the Ludwieg tube wind tunnel with an intermittent blowdown wind tunnel are presented in Reference 1. The results of the AEDC study, as presented in Reference 1, clearly show the advantages of the Ludwieg wind tunnel for obtaining the desired performance range (Mach numbers from 0.2 to 3.0 and unit Reynolds numbers of the order of 2×10^8). A comprehensive description of HIRT is beyond the scope of the present report; however for the purpose of clarity and continuity, the basic features of the facility are presented herein.

A schematic of HIRT is presented in Figure 1 and an artists conception of the facility is presented in Figure 2. The facility consists of a charge tube which is 1660 feet in length and 12.8 feet in diameter. Various support fixtures, a shut-off valve, a 5.5 million pound thrust fixture, and other components are attached to the charge tube. For the present design, the charge tube exhausts through a converging nozzle and 8 x 10 foot test section. The walls of the test section are of a variable porosity design to provide optimum flow conditions at transonic speeds. Suction through the walls of the test section is provided by a plenum evacuation system which surrounds the test section. The test section is followed by a diffuser which contains a traversing center plug for varying the mass flow through the test section. (The diffuser center body is not shown in Figure 1.) The walls of the diffuser also provide for transition from the rectangular test section geometry to a circular cross section. The valve manifold follows the diffuser and consists of 34 valve ports to which the starting valves are attached. This facility is designed to operate at transonic Mach numbers with charge pressures ranging up to 770 psi and a charge temperature of -30° F. During steady flow conditions, the maximum effective total pressure will be approximately 500 psi.

Flow through the test section is established by the instantaneous opening of the 34 exhaust valves located around the exhaust manifold downstream of the test section. Rarefaction waves propagate upstream into the charge tube setting the gas in motion and lowering the pressure and temperature.

The gas flows through the contraction into the test section. The test section Mach number is determined by the open area at the diffuser choke point located behind the test section and by the auxiliary suction through the porous test section walls. As the exhaust valves are opened, plenum chamber suction is begun in order to achieve steady flow in the test section. Between the starting time and the time at which the leading rarefaction wave (reflected from the end of the charge tube) arrives at the test section, useful testing may be done at essentially constant reservoir

conditions. The useful test duration of the Ludwieg tube facility is proportional to the supply tube length, and the reservoir conditions are dependent on the initial conditions in the charge tube as well as the controlled strength of the rarefaction wave which propagates through the tube.

At the exhaust valves, the instantaneous opening of the valves causes a system of shock waves to propagate through the valve exits into the exhaust stack and, subsequently, into the free field. The starting shock waves are followed by high speed jet flow. Both the starting shock transient and the jet exhaust are potentially hazardous noise sources. The characteristics of the noise environment associated with the operation of the facility and its impact on the environment are of primary importance in the present study.

3.0 NOISE CHARACTERISTICS OF HIRT

Detailed theoretical and experimental studies of the HIRT noise environment have been performed and the results are reported in References 2 and 3. Two primary noise generation mechanisms have been evaluated; 1) the starting impulse resulting from rapid opening of the flow starting valves, and 2) the short-duration, steady-state jet exhaust flow corresponding to the run duration of the facility. These two noise generation mechanisms have been treated as separate environments even though they occur in close sequence with the starting noise immediately preceding the steady-flow noise. The starting environment will produce a shock wave which will exhibit noise characteristics similar to an explosive blast wave or sonic boom in the far field, whereas the steady-state noise will resemble a rocket or jet engine exhaust environment. The most significant effect of the starting environment is the short rise-time with which the noise reaches maximum intensity. The model experiments, reported in Reference 3, were designed to simulate only the steady-state exhaust flow noise with no provision to simulate the starting shock environment. Therefore, the noise predictions for the starting process of the full-scale HIRT facility are based on theoretical analysis of this environment. On the other hand, the noise predictions for the steady-state exhaust flow are based on model experimental observables, supplimented by theoretical predictions.

Theoretical computations of the starting shock environment are presented in Reference 2 and Appendix A. The results presented in Appendix A are considered to be a more accurate prediction of the starting noise environment and these results will be used in the assessment of environmental impact. The results of the model experiments to define the steady-state exhaust flow noise are presented in Reference 3. Summaries of the noise characteristics for the starting shock environment and the steady-state exhaust flow environment follow.

3.1 Starting-Shock Environment

The HIRT flow-starting process is that of a constant mass flux source turned on in a time of 50 msec or less. This starting time is short compared to the total running time of approximately three seconds. The noise produced by the HIRT starting process has been predicted using a sonic-boom model of the starting process (see Appendix A). Pertinent results and conclusions defining the starting noise environment are as follows:

3.1.1 Overpressure

The overpressure of the starting shock wave is given by:

$$\frac{P - P_1}{P_1} = \frac{\dot{m}}{0.2\pi r P_1} \tag{1}$$

where $\dot{m}$ = mass flow rate with exhaust valves at full-open conditions

r = radial location

P_1 = ambient static pressure

For the most extreme operating condition of HIRT, $\dot{m}$ = 165,000 lb/sec, and the overpressure is given by:

$$\left.\frac{P - P_1}{P_1}\right)_{max} = \frac{3.86 \text{ ft}}{r}$$

The variation of maximum absolute overpressure, $\Delta P = P - P_1$, with radial distance from the exhaust stack is shown in Figure 3. Two curves are presented 1) the overpressure variation for an instantaneous valve opening (zero starting time) and 2) the overpressure for a probable valve opening time of 50 msec.

The maximum overpressure occurs at the valve throat (r_0 = 2.64 ft effective radius) and the absolute overpressure is:

$$\left.\Delta P\right)_{throat} = 21.5 \text{ psia}$$

3.1.2 Impulse

The starting-shock impulse can be an important factor in determining damage. This characteristic of the starting process is given by:

$$I = \frac{\dot{m}}{4\pi r} \tag{2}$$

It should be noted that the impulse depends only on $\dot{m}$ and does not vary with valve opening time. For the most extreme operating conditions of $\dot{m}$ = 165,000 lb/sec, the impulse is given by

$$I_{max} = 407 \ \frac{\text{lb - sec}}{\text{ft}^2} \ \frac{\text{ft}}{r}$$

The variation of maximum impulse with radial distance is shown in Figure 4.

3.1.3 Spectra

Starting-shock spectra for two typical radial locations are presented in Figures 5 and 6. The spectra are presented as dB per Hertz bandwidth relative to the overpressure. Ground attenuation and air absorption do not affect shock-wave propagation to any significant degree over the range of distances considered herein; however, there will be a variation in spectrum shape with distance due to the change in the overpressure signature (see Appendix A). The variations and trend shown in Figures 5 and 6 are typical of the effect of signature on spectrum shape.

In general, shock wave spectra are not very useful in assessing the effect of the shock wave on structural damage and subjective response since the passage of the shock wave produces a single noise impulse rather than a continuous noise signal. The overpressure and impulse are commonly used for analysis purposes. However, the shock spectra do reveal general characteristics of the energy concentration as a function of frequency with large energy levels at relatively low frequencies.

3.2 Steady-State Exhaust Flow Noise

The steady-state exhaust flow noise for the full-scale HIRT facility have been defined from model test results (see Reference 3). Extrapolation of the model test results to full-scale conditions resulted in the following predicted noise environments.

3.2.1 Overall Acoustic Power Level

The overall acoustic power level of exhaust flow environment for the full-scale HIRT facility is given by:

$$\mathrm{OAPWL} = 103.5 + 20 \log \dot{m} \quad , \quad \mathrm{dB\ re:}\ 10^{-13}\ \mathrm{watts} \qquad (3)$$

where

$\dot{m}$ = full-scale HIRT mass flow rate in lb/sec

The overall acoustic power level of the HIRT facility at the designed maximum mass flow rate of 165,000 lb/sec is predicted to be 207.9 dB, re: 10^{-13} watts. The overall power level will decrease 6 dB per halving of mass flow rate as shown in Figure 7.

3.2.2 Overall Sound Pressure Level

The overall sound pressure level for the full-scale HIRT facility, including the effects of air absorption and ground attenuation on sound propagation is given by:

$$\text{OASPL} = 52 - 20 \left[\left(\log \frac{r}{104} \right)^2 + 0.10 \right]^{1/2} + 20 \log \dot{m}$$

$$- \alpha(r) - \beta(r) \qquad , \qquad \text{dB} \ , \quad \text{re: } 0.0002 \text{ dynes/cm}^2 \qquad (4)$$

where

$\dot{m}$ = HIRT mass flow rate in lb/sec

r = radial location in feet

$\alpha(r)$ = air absorption loss, dB

$\beta(r)$ = ground attenuation loss, dB

The above equation is applicable to the sideline noise radiation in a plane corresponding to the HIRT exhaust stack exit plane, and includes near field shielding effects produced by the exhaust stack.

The variation of overall sound pressure level with radial distance from the exhaust stack is shown in Figure 8 for the worst-case condition of maximum mass flow rate. The various curves represent 1) HIRT noise in the absence of ground attenuation and air absorption losses which, for the far field, approaches inverse square law spreading of the noise field, 2) HIRT noise with air absorption losses, 3) HIRT noise with combined air absorption losses and ground attenuation losses for winter vegetation, and 4) HIRT noise with combined air absorption losses and ground attenuation losses with summer vegetation. Air absorption losses will always be present under practical conditions so curves 2, 3 and 4 are representative of HIRT noise levels surrounding the facility. Curve 2 is representative of cleared terrain and may be taken as an upper limit for the noise field. Generally, noise levels may be expected to range between the limits of curve 2 and curve 4, depending on the line-of-sight terrain conditions between the observer and the exhaust stack. These arguments are pertinent to low-wind conditions. The effects of wind are discussed in Appendix C.

It should also be noted that the results presented in Figure 8, which include air absorption and ground attenuation effects (curves 2, 3, and 4), supersede corresponding results presented in Figures 32 and 33 of Reference 3. These new data are based on more accurate analyses of the losses resulting from air absorption and ground attenuation as discussed in Appendix B.

3.2.3 One-Third Octave Band Spectrum

The one-third octave band spectrum of the exhaust flow noise, relative to the overall sound pressure level, is presented in Figure 9. This spectrum represents the sideline noise radiation in the near field in the absence of ground attenuation and air absorption. The effects of ground attenuation and air absorption are discussed in Appendix B. This appendix should be consulted for an analysis of the effect of the losses on the HIRT noise spectra.

4.0 SPECIFICATION OF ACCEPTABLE NOISE LIMITS

4.1 Human Impact

4.1.1 Factors Affecting Human Reaction

Loudness and Noisiness

An important property of an audible sound is its apparent magnitude. Human hearing is most acute at frequencies around 3000 Hz, and hearing acuity decreases gradually at lower and higher frequencies. Figure 10 shows the approximate response of the human ear. Thus, the way a given noise will sound depends on how its energy is distributed along the frequency spectrum. A simple method of determining the loudness of a sound is the A-weighting scale. The spectral intensity of the sound is divided into octave or one-third octave bands, each is weighted according to the A-scale shown in Figure 10, and the weighted intensities summed. The result is the magnitude of an "equally loud" 1000 Hz tone, in dBA. This weighting process is performed by the A-weighting circuit of a sound level meter. For sounds whose spectral contents are not extremely different, the dBA scale provides a reasonably good measure of loudness. More elaborate calculation schemes have been devised (References 4-8) for which calculated loudness of sounds with widely differing spectra correlate well with subjective judgment. The calculation methods for these schemes are similar to that for the PNdB scale described below.

In judging human reaction to noise, it has been found that "noisiness" or "acceptability" is a better measure than loudness. Figure 11 shows contours of equal perceived noisiness, after Kryter and Pearsons (Reference 8). The unit of noisiness is called the noy. A sound judged subjectively equal to an octave band of random noise centered at 1000 Hz with a sound pressure level of 40 dB is given a value of 1 noy; a sound judged to be twice as noisy is 2 noy, etc. To calculate the noisiness of a given sound, the octave or one-third octave band spectrum is needed. The noy value, n_i, of the i-th band is found from Figure 11, and the total noisiness is found by

$$N = n_{max} + K \left[\sum_i n_i - n_{max} \right]$$

where n_{max} = noisiness of the loudest band; K is 0.3 for octave bands and 0.15 for 1/3 octave bands. Perceived noise level, PNdB, is then the SPL from Figure 11 for this noy value at 1000 Hz. Analytically, the relation between N and PNdB is

$$PNdB = 40 + 10 \log_2 N$$

Among the commonly used methods for estimating perceived noise level, PNdB based on one-third octave bands is generally the most accurate (Reference 9).

Elaborate scales such as PNdB are useful for comparing annoyance of widely differing sounds. For sounds with the same spectral characteristics, simpler scales, such as dBA, are equally good. Botsford (Reference 10) has shown that for many broad spectrum noise sources (factory, vehicle, and neighborhood noises) the spectral characteristics can be represented by [dBC-dBA], where dBC is the summation of spectral band intensity without any weighting factor. For [dBC-dBA] near zero, noise is concentrated within the audible range, while for [dBC-dBA] large, the bulk of acoustic energy is below the most sensitive range of human hearing. For the noises examined in Reference 10, [dBC-dBA] ranged from 0 to 20. Figure 12, based on Reference 10 and extrapolated lower by about 10 dB, shows the relation between dBA and PNdB for [dBC-dBA] equal 0 and 20. The standard deviation of the correlation is 1 dB. This curve will be useful later in converting available community reaction data, often given in dBA, to PNdB. Also, if the spectrum remains substantially the same, the dBA scale of a sound meter is completely adequate for monitoring noisiness.

Noisiness of Impulsive Sounds

Noise rating scales such as perceived noise and dBA are based on subjective human response to steady noises of at least several seconds duration whose spectral characteristics are relatively constant throughout the duration. The experimental basis for these scales do not directly include waveforms like the HIRT starting wave, which is similar to a sonic boom. High frequency components are concentrated in the shock wave at the onset of the wave, while low frequency components are in the expansion region following the shock. It was shown by Zepler and Harel (Reference 11) that annoyance of sonic booms correlates with shock wave rise time as well as amplitude.

Waves with faster rise times were found to be subjectively noisier. Since faster rise times mean more high frequency spectral content (which lies in the range of human hearing for typical rise times), this suggests that noisiness of impulsive sounds may be predicted by their spectral content. Zepler and Harel calculated the annoyance of booms by using the phon scale (similar to perceived noise level discussed above). Figure 13 shows agreement of predictions with subjective evaluation. Pease (Reference 12) performed a similar analysis and presented a chart, Figure 14, for equivalent loudness of sonic booms as a function of overpressure and rise time. Total duration of the boom has little effect on loudness, as the frequencies involved are below the range of human hearing.

The rise time of weak shock waves is known to vary with overpressure. However, the mechanism is dependent on atmospheric conditions, and some details of the theory are still somewhat controversial. Analytic predictions of rise time cannot, at this time, be made with the same confidence as overpressures. Rather than calculate overpressure and rise time, then predict loudness from Figure 14, a correlation will be drawn from paired comparison data between sonic booms and subsonic aircraft noise. As shock

waves are generally more annoying when heard indoors, the correlation will be made for booms heard indoors. Figure 15 shows subjectively equivalent sonic booms and aircraft noise from References 13 through 18. Filled in data points represent outdoor comparisons. All other points are indoors, with sound levels measured outdoors. A line has been extrapolated through this data. The slope of this line is chosen to agree with Lundberg's (Reference 19) correlation of indoor comparison data from Reference 12. It should be noted that the correlation drawn in Figure 15 has loudness scaling approximately with sound pressure levels to the 3/2. Annoyance from outdoor booms scales closer to overpressure to the 5/2 (Reference 19). Since building response is dependent on impulse, which is proportional to overpressure, this supports the usual assertion that indoor annoyance depends to a large extent on building vibration.

By means of Figure 15, a shock wave of known overpressure can be assigned an equivalent perceived noise level on the PNdB scale.

Startle Effect of Shock Waves

One of the most bothersome psychoacoustic effect of shock waves is that they are startling. Figure 16 summarizes the results of a community survey made during the Oklahoma City sonic boom tests, Reference 20. The percent of population who were more than a little annoyed is shown versus shock overpressure, with annoyance divided into several categories. The greatest annoyance, except for house rattling, was from being startled. In addition to annoyance, a number of claims have been filed for damage allegedly caused by startle reactions (Reference 21). Typically, a person is engaged in a delicate task when startled, such as a Chicago man who punctured his eardrum while cleaning his ear at the time of a boom. Part of a startle reaction is increased muscular tension; it is conceivable for injuries to occur directly from muscle tension. Although damage from startle reaction to booms has been relatively rare (Kryter, Reference 22, has remarked that it is perhaps surprising that there have been so few claims of injury), it must be taken into account in assessing community reaction and effect on AEDC personnel.

Laboratory Startle Experiments — Lukas, Kryter and others (References 15, 16, 23, 24) have conducted a series of experiments to determine the startle reaction to simulated sonic booms and other noises. In the first of these, a group of nine subjects were told that they were to listen to music for ten minutes. Ten sonic booms were then included with the music. Heartbeat was monitored. It was found that the booms had little consistent effect on heartbeat, except for some subjects who showed a sharp increase in heart rate to the first boom. Reaction to later booms was very small. It was concluded that the subjects had adapted to booms. However, seven out of nine said that after the first boom they expected to hear others, so that it may be more reasonable to conclude only that there is little startle reaction to expected booms.

In later experiments (References 16, 23, 24) subjects were subjected to sonic booms up to 2.5 psf and other noises while performing a tracing task. The tracing task consisted of following a narrow track on a board with a stylus. An electrical circuit through the

stylus and track recorded time off track. Bipolar electromyographic (EMG) activity in the trapezius muscle was also monitored. Negligible startle reaction was found for 100 dB subsonic aircraft noise.

A definite reaction, with impairment of tracing performance and increased EMG reaction, was generally found for sonic booms. An important result was that one group of test subjects (Reference 24) showed no significant reaction to sonic booms. This group consisted of tool and die makers and machinists, who were accustomed to noisy environments, while the other groups consisted of students and technical and professional personnel whose normal work environments were relatively quiet. It was suggested that simulated sonic booms did not differ appreciably from noises commonly found in machine shops. Consequently, there was little startle reaction from subjects accustomed to such environments. This supports the conclusion that people can adapt to sonic booms, although adaptation is highly subjective and may vary greatly between individuals. The lack of a startle response for machinists is very significant for HIRT. One of the nearest buildings, subjected to starting waves up to 2 psf, is a machine shop. For this building, then, it is not likely that work performance will suffer due to the starting shock. Kryter (Reference 22) has also suggested that a person concentrating on a delicate motor task is less likely to be startled than a relaxed person. For this reason, and because the psychoacoustic impact of the steady noise is generally greater than for the starting shock, it is felt that the startle effect of the starting shock, as a phenomenon distinct from annoyance, will pose no additional problems.

Duration and Onset

Kryter and Pearsons (Reference 8) conducted tests to measure the effect of duration. Pairs of sounds with different duration were presented to subjects, who were asked which of the pair was more disturbing. The range of durations was 1.5 to 12 seconds. This was subsequently extended by Pearsons (Reference 25) to 64 seconds. Onset (rise time) of the signal varied from 0.5 to 4 seconds and was found to not significantly affect the judgments. Figure 17, taken from Reference 26 summarizes their results. In the range of 1.5 to 4 seconds, the correction is 6 dB/doubling in duration, while for duration over 12 seconds the correction may be as little as 2 dB/doubling. The average is 3 dB/doubling. This average corresponds to equal noisiness for equal total acoustic energy.

The results of Kryter and Pearsons show that signal rise time is not an important factor in noisiness for rise time greater than 0.5 seconds. In Reference 27, shorter rise times were investigated. Pulses of duration 0.7 to 1.0 sec, with rise times of 0.03 to 1.0 sec, were judged in a paired comparison test. Spectra of the pulses included pure tones, narrow band, octave band, and wide band noise. A statistically significant change in relative level of about 1 dB was found for rise times varying from 0.03 to 0.5 sec. This effect on perceived noisiness of rise time is negligible for all practical purposes.

Frequency of Occurance

If one noise event causes a certain human impact, it is reasonable to expect two events to cause a greater impact. If the results of duration discussed above are assumed to apply to the total "on-time" of a noise, then the impact of a series of noise events may be taken to be the same as for a single event with acoustic energy equal to the total of the series. This assumption is applied to most of the noise rating scales discussed in subsection 4.1.2. Some scales are based on greater annoyance for a series of noise events than just equal energy, but no one summing method appears to provide more accurate predictions in this respect. This will be discussed later when the various rating scales are compared.

Time of Day Occurance

The impact of noise varies with time of day, primarily because of activities associated with time of day. Generally, background noise levels are lower at night because of decreased activity, so that there is less "masking" of other noises. Different levels are also required for different activities. In section 4.1.3, where acceptable limits will be determined, it will be shown that the noise threshold is lower for sleep disturbances than for speech interference, which in turn is lower than for interference with certain work activities. This means that a factory worker, for example, will tolerate one noise level at work, requires a lower one while home with his family in the evening, and yet a lower one while sleeping. It is generally accepted that 10 dB lower levels are required at night, based on data to be presented in Section 4.1.3. Occasionally a 5 dB factor is used for evening.

4.1.2 Noise Rating Scales

There are a number of community noise rating scales in the literature which combine the above factors into a single rating. Just as the perceived noise level combines spectral data into a single value so that different types of noises can be compared, the community rating scales normalize duration, frequency, etc., so that different noise environments can be rated on the same acceptability scale. Ratings are generally based on corrections to perceived noise level of a single event, PNL, in PNdB or some similar quantity. They can be generally written as

$$\text{Rating} = \text{PNL} + A \log \frac{t}{t_{ref}} + B \log \frac{N}{N_{ref}} - C \tag{5}$$

where t = duration of a single event, N = number of events per day, t_{ref} and N_{ref} are reference duration and number, and A, B and C are constants. For the principle of equal annoyance for equal total energies, $A = B = 10$. The constant C is an arbitrary number used to normalize the rating to some aesthetically pleasing origin, and varies from system to system. An additional factor for day and night is added, with night events usually being considered 10 dB noisier. When $A \neq 0$,

$PNL + A \log t/t_{ref}$ are considered together as EPN, equivalent perceived noise level. Table I, adapted from Reference 28, summarizes the various rating scales in use, cast in the form of Equation (5). The scales differ between choice of PNL or EPN, and for several, B is greater than 10. In Reference 28, a comparison is made between these scales, and it is shown that they correlate well with each other. The exact computational method and flexibility of the various scales varies. For example, the frequency factor in CNR (Community Noise Rating) is quantized over ranges of flight numbers, i.e., 0 for 10 to 20 flights, +5 for 31 to 100 flights, etc. (Reference 29), while NEF (Noise Exposure Forecast) provides a continuous correction (Reference 30). The choice of scale therefore is decided on the needs of computational convenience and flexibility. The NEF scale, which is essentially a refinement of CNR, provides for events of different loudness and time of day. Because of its flexibility, and its common usage in this country for airport noise, HIRT community annoyance will be based on NEF.

Noise Exposure Forecast, NEF

The NEF rating, as described in Reference 30, is based on the following computation:

1) For each type of noise event (i.e., aircraft type and runway number for airport noise, or total pressure for HIRT),

$$NEF_i = EPN_i + 10 \log_{10} \frac{N_i}{K} - C \tag{6}$$

where

$$EPN_i \doteq PNL_i + 10 \log_{10} \frac{t}{15 \text{ sec}}$$

K = 20 daytime
1.2 night

N_i = number of events

C = 75

TABLE I

COMPARISON OF NOISE RATING SCALES

COUNTRY	SCALE	DEFINITION
U.S.A.	CNR	$= PNL + 10 \log_{10} N - 12$
U.S.A.	NEF	$= EPN + 10 \log_{10} N - 88$
France	$\mathcal{N}$	$= PNL + 10 \log_{10} N - 30$
Great Britain	NNI	$= PNL + 15 \log_{10} N - 80$
Germany	$\overline{Q}$	$= PNL + 13.3 \log_{10} N - 52.3$
South Africa	$\overline{NI}$	$= PNL - 13 + 10 \log_{10} N - 39.4$
Netherlands	B	$= \frac{20}{15} (PNL - 13) + 20 \log_{10} N - C$
I.C.A.O.	WECNL	$= EPN + 10 \log_{10} N - 39.4$

PNL_i is the perceived noise level in PNdB of events of type i, including pure tone corrections. The day and night values of K are based on nighttime noise being 10 dB more annoying than daytime, with night defined as 10 P.M. to 7 A.M. The value C = 75 is selected in Reference 30 because judgment tests of annoyance have indicated that noise of 70 PNdB for 20 to 30 times a day is "of no concern" or "not noticeable" (Reference 31). Reference 30 shows that for a jet transport with PNL = 70 PNdB, EPN = 75. For airport noise, then, this value of C makes NEF = 0 the threshold for noise intrusiveness.

2) NEF_i for each type of noise event are added on an energy basis to give the overall NEF:

$$NEF = 10 \log \sum_i 10^{\frac{NEF_i}{10}} \qquad (7)$$

This value of NEF is then used to determine community acceptability. Values for the area surrounding AEDC will be recommended in the next section. It should be mentioned that these recommended values will be somewhat lower than those usually set for areas around urban airports, where the objective is often to minimize complaint response, with the result of few formal complaints but considerable annoyance.

4.1.3 Limits for Human Impact

The NEF rating scale provides a single number representing the noise environment, such that different noise environments with the same NEF value will have the same impact on communities. Different communities will have different requirements. In this section, limits for the AEDC community will be established.

There are three groups of people to consider:

- Residential areas outside AEDC
- AEDC personnel, except for HIRT
- HIRT operating personnel

The first two categories are communities of two different types, and limits for NEF will be established. The third group falls in the class of industrial noise exposure, and acceptability is achieved by conforming to the standards required by the Walsh-Healey Act. We will begin with a discussion of the residential area.

Residential Noise Limits

Acceptability of noise in a residential community depends on the following factors:

- Interference with sleep
- Interference with conversations and similar activities (TV watching, theaters, etc.)
- Physiological harm to residents

This last factor is not unrelated to the first two, as psychological stresses often lead to physiological harm over long periods.

There are two ways of assessing the interaction of noise and a community. The first is the effect of noise on the community, while the second is the reaction of the community to the noise. If genuine good relations with the community are desired, the first is the proper viewpoint. Quite often, as in the case of large metropolitan airports, it is necessary to take the second viewpoint, and limits are established which stop just short of provoking organized community action and lawsuits. Because good relations with the surrounding community are felt to be important in the present case, the limits discussed below are based on the first viewpoint. They will be compared to limits usually deemed acceptable for airport noise.

Sleep Disturbance — Sleep disturbances caused by noise often occur without the sleeping person's knowledge. Noise which is not sufficient to arouse the sleeper may impair the quality of sleep by shifting him from a deeper stage of sleep to a shallower stage, or by depriving him of a sufficient amount of the portion of sleep period which is connected with dreaming and is thought to be important to rest. Such deprivation can lead to increased irritability, or more serious side effects in extreme cases. It is therefore important to consider shifting of sleep stages as well as actual awakening.

A number of laboratory experiments on sleep have been performed by studying the subject's brain wave patterns with an electroencephalogram (EEG). Other laboratory experiments have been performed in which actual awakening of the subjects was the only means of observing sleep disturbance. Further information on sleep disturbance by noise (particularly aircraft noise) comes from community annoyance surveys, in which each person is asked to complete a detailed questionnaire (including questions on how frequently he is kept from going to sleep or is awakened by noise) and the noise characteristics of the environment are also measured. Results of several of these studies are discussed below.

Grandjean (Reference 32) studied the disruption of sleep by noise among 343 persons sleeping in their bedrooms, observing only actual awakening, without benefit of EEG traces. He used noise without any sudden changes of volume and in which equal energy existed across the whole frequency spectrum. The sounds he used (converted to PNdB) produced the following results:

TABLE II

RESULTS OF GRANDJEAN'S SLEEP EXPERIMENTS

Level of Disturbing Sound, PNdB	Percent of Subjects Awakened
43	10
50	23
57	40
63	50

A study of sleep through recording of brain wave patterns was made by Thiessen (Reference 33), using the recorded noise of passing trucks, at levels ranging upward from 49 PNdB. He found that at levels between 49 and 56 PNdB, 10 percent of the subjects either shifted to a shallower stage of sleep or awakened; at a level of 62 PNdB, 50 percent of the subjects either shifted to a shallower stage or awakened.

Another study of sleep disturbance with recording of brain wave patterns was made by Lukas, Dobbs and Kryter (Reference 18). Subjects were exposed to subsonic aircraft noise of 10 seconds duration, and indoor noise levels from 68 PNdB to 96 PNdB. The following awakening results were obtained for adults:

TABLE III

AWAKENING BY AIRCRAFT NOISE (REFERENCE 18)

Level of Disturbing Sound, PNdB	Percent of Subjects Awakened	Equivalent Steady Noise, PNdB
68	0	30
77	15	39
82	19.5	44
88	29.8	50
96	36.2	58

The last column represents the disturbing noise normalized to a 24 hour average, according to the methods of the noise rating scales discussed in the previous section. This enables a direct comparison with Grandjean's data, which was for a more or less steady noise disturbance. Figure 18 compares the results of these three studies, showing both normalized and raw data for the last.

A study in London (References 34 and 35) related noise exposure to various activities disturbed as reported by 1730 persons in a survey. The responses were related to a noise rating scale which includes both noise magnitude and number of events. Figure 18 shows their sleep disturbance response for about 30 flights per day.

Also shown in Figure 18 is the equivalent Noise Exposure Forecast. The NEF values on the scale represent equivalent outdoor noise levels (taken to be 20 dB higher than indoor, a typical frame house attenuation value) at night.

From Figure 18, it is apparent that as noise level is increased, an increasing fraction of the population can be expected to experience sleep disturbance. Above 40 PNdB (NEF = 20), 15 percent or more of the population may be awakened, while above 50 PNdB at least 20 percent awakening should be expected. It should be kept in mind that awakening is highly subjective, resulting in considerable scatter in individual response. Age is an important factor. For example, in Reference 18, awakening response at 77 PNdB (39 PNdB normalized, NEF = 19) ranged from 0.7 percent for children 5 to 8 years old to 22.7 percent for senior citizens 69 to 75 years old. The following are awakening data for the senior citizen group in Reference 18:

TABLE IV

AWAKENING OF SENIOR CITIZENS

Level of Disturbing Sound, PNdB	Equivalent Steady Noise, PNdB	Percent Awakening 69-75 Years
77	39	22.7
82	44	26.9
88	50	33.3
96	58	46.6

Based on the data in Figure 18, with special notice to old people (who may suffer more harm from a given level of sleep disturbance than young people), the threshold of sleep disturbance is approximately NEF = 5. Below this level, sleep disturbance should not be a problem, and this limit is recommended. A maximum tolerable limit would be NEF = 15. Above this point, serious sleep disturbance would occur, especially among old people. This upper limit represents a point where complaints might be expected to begin, and is not a desirable long term situation. Community reaction to such conditions will be discussed shortly.

Interference with Speech Communication - Noise can interfere with speech communication by preventing one's hearing some of the words or sentences being communicated. Speech communication includes direct communication between speaker and listener (such as conversation and classroom lectures) and includes listening to television or radio and telephone communication.

The speech interference effects of noise have been thoroughly studied and well documented, and criteria for designing environments for good speech communication have been a standard tool of acousticians and architects for many years in the design of offices, classrooms, auditoria, etc. The criteria which have been developed are expressed in terms of the "speech interference level" (SIL) of the interfering noise. The range of frequencies most important to speech communication is comprised of the three octave bands centered at 500, 1000 and 2000 cycles per second (or Hertz), and the magnitude of a noise can be expressed in terms of the noise level (in decibels) in the SIL scale, by the average of the octave band sound pressure levels in the three octave bands.

The ability of a speaker and listener to continue good communication in spite of an interfering noise depends not only on the magnitude and tonal characteristics of the noise but also on the volume of the speaking voice and on the distance between the listener and the speaker. Standard curves have been published, based on the accumulation of much experimental research, which show the noise limits to be set for various speaker-listener distances.

Table V, based on data in Reference 36, gives levels in PNdB of the maximum noise levels permitting normal conversation, without raised voices, at several distances.

TABLE V

Distance Between Speaker and Listener Feet	Level of Interfering Noise PNdB
1	90
2	82
4	76
8	70
10	69
16	65

The values in this table represent the limiting case, and more reliable and complete understanding of communication in a conversational tone could be achieved at slightly lower levels of the interfering noise.

From information on typical speaker-listener distances in the rooms involved (such as living rooms, family rooms or classrooms), a noise limit can be set which provides for good, uninterrupted speech communication. This basis for setting of limits is extremely important in the residential application, since (as will be seen later) it constitutes the most restrictive criterion for daytime activities typical of residential areas. In general, a typical listener-speaker distance in homes does not exceed 10 feet for a normal conversation, and one would therefore tend to limit the level of any frequently occurring interfering noise to 69 PNdB or less in living rooms, family rooms, etc. This also corresponds to the background level at which people tend to raise their voices, and may therefore be considered to be the threshold of annoyance.

A level of 69 PNdB corresponds to NEF = 19. For indoor listening, assuming 20 dB structural attenuation (typical frame house), NEF = 39. These limits represent an upper limit for community tolerance, and levels 5 to 10 dB lower would be preferable. Based on speech interference, recommended community exposure is NEF = 10 to 15, with NEF = 20 considered to be the threshold of annoyance. Note that sleep disturbance is a more critical factor than speech interference.

There may be some question as to the validity of applying speech interference criteria to a short duration noise. Speech interference levels are basically presented in terms of steady noise levels which make communication difficult. An intuitive assumption for intermittent noise sources such as HIRT might be that speech would not be interrupted for very long at any one time, so that arbitrarily loud noises could be tolerated for very short times. However, examination of community response to sonic booms over Oklahoma City (Reference 20) provides evidence that speech interference criteria may be applied to even impulsive noises whose total on-time is negligible. Figure 16 shows the annoyance response of the population as a function of average overpressure, eight (8) sonic booms per day. A noticable fraction of the population was annoyed because of speech interference. The NEF value for this boom exposure is 29 (Reference 37). The observed community response at this value corresponds well with expected response based on the threshold of NEF = 19 for speech interference. The communication disruption due to a short, high intensity, impulse is therefore just as significant as the interference from background noise with the same energy per day.

Physiological Effects of Noise — In addition to sound induced hearing losses (which will be discussed in the section related to protection of HIRT personnel, and are not as restrictive as community considerations), exposure to noise can induce physiological reactions due to stress. There have been a number of experiments reported on the ability of noise to produce measurable physiological stress reactions. These stress reactions derive from a widespread activation of the autonomic nervous system, resulting in changes in salivation, gastric activity, heart rate, respiration rate, blood vessel diameter, pupil size and sweat gland activity. Experiments to establish some of the kinds of stress reactions which can be induced in animals and humans by exposure to noise are typified by References 38 through 45.

Many of the experiments have used stimulus sounds at levels well above the region of interest here. However, the indications of the experiments at noise levels more ordinary to everyday experience do reinforce the (lower) levels required for a good speech communication environment. Jansen (Reference 45) has tentatively concluded from his own experiments that the threshold of stress response is at sound pressure levels of about 75 dB and that reactions become pronounced at 90 to 95 dB, with 95 dB marking the beginning of injury. The threshold of 75 dB corresponds to about 100 PNdB for wide band noise, and 90 dB wide band noise corresponds to 118 PNdB. Jansen proposes limiting any wide band noise exposure to 88 dB, about 115 PNdB.

There is a growing body of evidence that recurrent exposure to noise levels capable of inducing measureable stress reactions may produce physical health defects in a substantial portion of the exposed population. Attempts to gain insight into this question have produced results which would encourage conservatism in the setting of noise limits. For example, a Swedish study of traffic noise (Reference 46) has shown that symptoms such as headache, insomnia, and nervousness are so well correlated with the noise exposure that one can use the intensity of annoyance as an index of the severity of the exposure. There is reason to suspect that periods of exposure to stress (including noise as a stressor) may temporarily alter the subject's resistance to infectious disease (Reference 47). The question of psychological effects has been raised by a British study (Reference 48) which implicated noise as a possible factor in increased rates of admission to mental hospitals. In this study, such factors as age, sex, marital status, population density, and socioeconomic status were reasonably well controlled, and the study (covering two years of admissions to a psychiatric hospital) showed significantly higher rates of admission from inside an area of maximum noise near London's Heathrow Airport than outside that area.

In a position paper for the American Association of Public Health on the effects of noise on health in the residential environment, Dr. John Goldsmith (California Department of Public Health) and Erland Jonsson (sociologist with the Swedish National Institute of Public Health) (Reference 49) recommended epidemiological studies of exposed populations in order to determine the health effects of noise-induced stress.

Thus far we know of only one study where the effects of aircraft-type noise on populations have been studied in terms of physical health effects. This was a study in the USSR, Reference 50, which contained the following elements:

1) Measurements were made of the noise at ground level around nine (unidentified) airports utilized by all the main types of Soviet civil aircraft, including turbojet, turboprop and piston-engine powered transport aircraft.

2) Health statistics concerning the same populations were collected and analyzed, and it was found that those residents within 6 kilometers (approximately 3.7 statute miles) of an airport had higher incidence (by a factor 2 to 4 times) of otorhinolaryngological diseases (otitis and auricular neuritis), cardio-vascular

diseases (hypertension and hypotension), nervous diseases (neuritis, asthenic states), and gastrointestinal disease (gastric and duodenal ulcers, gastritis), especially the young and middle-aged people. The brief summary report in the published literature, unfortunately, does not give the trend or distribution of these results as a function of the noise environment itself. We infer from their table of sound levels and distances, however, that the quoted distances are measured along the primary climb paths, from a point at the beginning of take-off roll. These studies were carried out for the adult population (over 15 years of age) by analyzing 145,000 diagnostic cards, and for the school children (9 to 13 years of age) by clinical examination in residential areas adjacent to airports and in a control area remote from airports.

3) The research team carried out physiological tests of 15 healthy subjects in the age range 21 to 30 years, by exposing them in a soundproofed chamber to tape-recorded noise of the TU-104 turbojet transport aircraft at 75, 85, 95 and 105 PNdB for 10 and 20 flights per hour. The physiological effects of the noise were studied by direct measurement of brain waves, pulse rate and pulse wave amplitude. Aircraft noise at 75 and 85 PNdB was found to have no effect, while 95 PNdB produced slight effects and 105 PNdB produced pronounced effects. Most of the effects which occurred at 105 PNdB for 10 flights per hour became more pronounced at 20 flights per hour. The kinds of effects found were decreases in pulse wave amplitude (due to constriction of the blood vessels) and depression of the electric activity of the cerebral cortex which caused increases in the latent period of response to both light and sound.

4) The subjective reactions of the populations surrounding the airports were studied by sociological survey (individual interviews using a questionnaire) including over 2000 persons in 22 urban and rural areas located within 40 kilometers (approximately 25 statute miles) of the airports.

From the combined results of all the foregoing studies, the Russian research team concluded that aircraft noise of 105 PNdB is not permissible in populated areas and recommended that maximum permissible levels be set at 100 PNdB in the daytime and 90 PNdB at night for populated areas.

Note that these limits are lower than those for direct physiological damage, but are still higher than the limits based on sleep disturbance and speech interference. Considering the growing evidence of long term health from repeated exposure to noise levels capable of inducing stress responses, it is fortunate that the health-related criteria which may emerge in the future are not as restrictive as the criteria related to sleep and speech communication, for which we already have a firmer data base.

Summary of Community Limits and Comparison with Community Survey — The NEF limits recommended above are summarized in Table VI:

TABLE VI

SUMMARY OF COMMUNITY NEF LIMITS,
BASED ON SLEEP, COMMUNICATION, AND HEALTH CRITERIA

	Recommended Limit	Maximum Tolerable Limit
Sleep Disturbance	5	15
Speech Interference	10	20
Long Term Physiological Harm	--	39

The physiological limit is based on 100 PNdB for events per hour assuming the events last 15 seconds each (typical for aircraft flyovers).

For comparison, Table VII shows Swiss and British noise standards (Reference 51) for different types of communities. The standards are given in dBA for background noise (the Swiss standards for intermittent noise are given in Reference 51, and correlate with the time scaling method of the NEF scale), and Table VII shows equivalent NEF values. In the case of the British standards, where indoor levels are specified, 20 dB attenuation by house structure is assumed.

The limits in Table. VI, based on speech interference, are in substantial agreement with the residential and country limits of Table VII. The lower limit based on sleep disturbance, which was chosen so that there would be almost no sleep disturbance, agrees quite well with Swiss hospital zone requirements. In hospital zones, where rest and sleep disturbance is a critical factor (Reference 52), a limit of NEF = 5 should be adhered to.

TABLE VII

SWISS AND BRITISH COMMUNITY NOISE LIMITS

Zone	Day (dBA)	Night (dBA)	Equivalent NEF
Swiss (Outdoor):			
Hospital	45	35	7
Quiet Residential	55	45	17
Commercial	60	50	23
Industrial	65	55	27
British (Indoor):			
Country	40	30	20
Suburban	45	35	26
Busy Urban	50	35	26-31

A measure of community annoyance is the number of complaints received. Figure 19, adapted from Reference 9, shows the relation between noise exposure and expected community reaction, based on a number of case histories in airport noise zones. The range of reactions, depending as it does on individual responses, is quite broad. Based on information such as in Figure 19, the following are the residential criteria recommended in Reference 30 for communities near airports:

TABLE VIII

CRITERIA RECOMMENDED FOR
COMMUNITIES NEAR AIRPORTS

NEF $<$ 0	No noise inteference
0 $<$ NEF $<$ 30	Some noise complaints are possible, and noise may interfere with some activities
30 $<$ NEF $<$ 40	Individuals in private residences may complain, perhaps vigorously; concerted group action is possible. New single family dwelling construction is to be avoided. If apartments are constructed, noise control features should be included in their design.
NEF $>$ 40	Residential use is incompatible

These limits are essentially based on complaint response. They are in good agreement with criteria summarized in Table VI, with the recommended limits based on sleep and speech interference falling into the rather broad 0-30 range of "some interference", and the physiological limit of 39 coinciding with the limit for residential use. (It is interesting, and agrees with the notion of survival reaction, that at noise levels leading to long term physiological harm even the most tolerant communities will organize to stop a noise source.) For airport usage, 30 is generally recommended as a residential limit. This is basically the point above which complaints and occasional lawsuits become a serious annoyance to the noisemaker. The percentage of annoyed people complaining is generally small. For example, in sonic boom tests over Oklahoma City (Reference 20), surveys revealed that 90 percent of the population experienced interference, 35 percent were annoyed, 10 percent felt like complaining, and less than one percent actually complained. A criterion such as NEF = 30, based on onset of serious complaints, has been described as "20 percent of the population much bothered" (Reference 53).

Based on the above discussion, the following are recommended limits for community noise, and the expected reaction:

TABLE IX

RECOMMENDED COMMUNITY NOISE LIMITS, AND EXPECTED COMMUNITY REACTION

	NEF	Recommended Usage and Expected Reaction
	0	No annoyance
Recommended Limits	5	Acceptable for hospital zones
Recommended Limits	10	No difficulties with residential use, although a small number of complaints are possible
Recommended Limits	20	Acceptable for residential use, but complaints should be expected as this level is approached. As this level is exceeded, complaints will increase.
	30	Numerous complaints, including group action, should be expected. Possibility of occasional lawsuits.
	40	Legal action expected. Incompatible with residential use on the basis of long term physiological harm due to stress reaction.

Within the 10 < NEF < 20 zone representing the limit for residential zones, special consideration should be given to schools and theaters. Unless specially soundproofed, these should perferably be situated at the lower end of this range.

AEDC Personnel

The criteria for acceptability by AEDC personnel not involved with HIRT is that their working efficiency not be impaired. AEDC personnel can be roughly divided into two groups, office workers and technician and laboratory personnel.

Office Personnel — Recommended noise limits for office workers, based on speech communication criteria, are well established. The following are steady noise limits for three types of office environments from Reference 54:

- Executive - 50 PNdB
- Secretarial (Typing) - 65 PNdB
- Drafting - 60 PNdB

If these maximum background levels are taken as representing the total tolerable acoustic disturbance (as was assumed in using speech interference as a residential criterion), then the NEF limits for office space, based on these figures, are:

		NEF
• Executive	-	20
• Secretarial (Typing)	-	35
• Drafting	-	30

These limits assume 20 dB attenuation by building structure with the NEF values specified above being outdoor limits at the building location. If greater soundproofing exists, then correspondingly higher NEF values will be acceptable.

Technician and Laboratory Personnel — The nature of the work conducted at AEDC in the performance of test programs, model and facility fabrication and construction, and maintenance functions is such that technician and laboratory personnel are subjected to a wide range of noise environments. Personnel involved in delicate tasks, such as instrument calibration, may be considered to be in the same category as office personnel. Machine shop workers and construction personnel are accustomed to quite loud noise environments. Reference 51 suggests a level in "workshops" of approximately 75 PNdB. Assuming 20 dB attenuation by building structure, this corresponds to NEF = 45. Noise in machine shops can average 10 dB higher; this corresponds to NEF = 55.

Construction and maintenance personnel spend a significant portion of their time outdoors. For any outdoor personnel at HIRT, an appropriate noise level is that tolerated at construction sites or in busy urban environments. A pneumatic drill 50 feet away has sound pressure levels of 85 dB (Reference 55); this corresponds to 80-90 PNdB. Noise levels of 85-90 PNdB are tolerated in busy urban environments. Taking 90 PNdB as a reasonable level for outdoor personnel, NEF = 40.

In addition to NEF limits for outdoor workers, such personnel must be protected from excessive single event noises. The single event limit for industrial workers, based on the Walsh-Healey Act, is approximately 125 PNdB (see next section). Any area subject to outdoor levels of this intensity (or preferably lower by a safety factor of 10 dB) should be restricted when HIRT is in operation. In summary, the following limits apply to technician and laboratory personnel:

		NEF		
• Workshops	-	45		
• Machine shops	-	55		
• Outdoor workers	-	40	,	Single event - 115 PNdB

HIRT Personnel

The noise exposure limits for HIRT personnel are based on hearing protection criteria. The limits for unprotected personnel are well established, and are specified by the Walsh-Healey Act (Reference 56). The noise limits are specified in dBA for different exposures per day, and are listed in Table X. These are the same limits as specified in the more recent Occupational Safety and Health Act of 1970; however, the Walsh-Healey Act is still in existence and is still fully effective.

TABLE X

WALSH-HEALEY ACT AMENDMENT VALUES

Noise Exposure Limits

Duration per Day, Hours	Sound Level, dBA
8	90
6	92
4	95
3	97
2	100
1-1/2	102
1	105
1/2	110
1/4 or less	115

HIRT will run a maximum of approximately 90 runs a day, at 3 seconds per run. This is a total of less than 1/4 hour, so that unprotected personnel must not be exposed to more than 115 dBA. For HIRT's exhaust spectrum, this corresponds to approximately 125 PNdB.

<u>Limits for Personnel with Ear Protection</u>

At sound pressure levels above those requiring ear protection, other parts of the body begin to show response to sound. The response depends on frequency, and is closely coupled to resonances of the various parts of the body. Vibration causing accelerations of more than 2 g at low frequencies can cause injury to bodily organs (Reference 57). The effects are most pronounced at low frequencies.

In experiments with subjects accustomed to high noise levels, Mohr, et al. (Reference 59) investigated the effects of high intensity, low frequency noise on personnel. At 100 Hz pure tone, 153 dB was found to be the limit of voluntary tolerance. Symptoms included nausea, headache, coughing, chest discomfort, and temporary loss in visual acuity. Most symptoms disappeared immediately after the test, although there was a marked degree of past exposure fatigue. No evidence of permanent damage was observed.

Although there appeared to be no permanent harm done to the subjects of Reference 58, it is felt that the temporary symptoms involved should be avoided. The limit of voluntary tolerance for pure tones ranged from 150 to 153 dB over a frequency range of about 35 to 100 Hz. For the broad spectrum HIRT noise, these effects should be avoided if personnel are restricted from zones with OASPL greater than 150.

4.2 Effect of Noise on Animals

The AEDC reservation surrounding the fenced facility complex is a multiple use area, serving the surrounding community as a wildlife preserve and hunting area. Outside the reservation, there are populated areas, including farms, with domestic animals (pets and farm animals). Consideration must be given to the impact of noise on domestic animals off the reservation and wild animals both on and off.

Information regarding the effect of noise on animals is not as abundant as for people. However, there is a sufficient amount available, often as a side product of human investigations, so that some general guidelines can be drawn. Much of the available information falls into three categories:

- Physiological studies on laboratory animals, for the purpose of extrapolating to humans. Examples of this type of work are References 39, 40, 59 and 60. Since conclusions as to the ill effects of noise on humans are based to some extent on such studies, it follows that animals have physical tolerance to noise similar to humans.

- Damage claims based on harm to domestic animals resulting from noise, generally sonic booms. Some reports by wildlife observers on harm to wild birds are also available. Bell (Reference 61) has reviewed the available literature pertaining to animal reaction to sonic booms.

- Field observation and laboratory experiments to assess animal reaction to sonic booms. Such studies were performed in conjunction with human response studies. Since human impact of sonic booms can be assessed by the same methods as for other noises, these studies provide a connection between psychacoustic limits for animals with those for people.

4.2.1 Domestic Animals

Except for an occasional pet temporarily on the reservation with its owner, domestic animals will be found only in residential areas. The recommended human safety factor for such areas is so large that no direct physical harm should result to animals. The only ill effects may result from injury due to startle reaction. For farm animals, productivity must not be adversely affected.

As part of the sonic boom test program at Edwards Air Force Base, farm animals subjected to sonic booms were observed for startle reaction (Reference 13). Overpressures at the animal location are not specified in Reference 13. On the basis of nominal flight track overpressures and distance from flight track, we estimate overpressures in excess of 1 psf. This corresponds to an equivalent perceived noise level greater than anticipated in any populated area for HIRT operating conditions.

The following observations were made:

1) Except for avian species, startle reaction was minimal. Reactions were of similar magnitude and nature to those resulting from flying paper, the presence of strange persons, or other moving objects.

2) No significant drop in production were noted, although the tests were not adequate to provide conclusive evidence. A claim was made for a drop in pheasant egg production, but it was not clear if this was due to booms or to unusually hot weather. Turkey egg production was normal.

3) The observed animals had been exposed to booms for several years; it is possible that they had adapted to booms.

The last point above indicates that even if animals initially show an adverse reaction to noise, they will adapt to it.

In addition to isolated incidents of animals injuring themselves due to startle reaction (Reference 21), there are two types of animal damage claims which received considerable attention. These are claims that chicken eggs failed to hatch, and claims that mink killed their young when startled. These two phenomena were carefully investigated under controlled conditions.

In experiments at Kelly Air Force Base (Reference 62), five sets of eggs, totalling 3415, were exposed to 30 booms per day, up to 19 psf outside the building housing the incubator. Hatch rate was normal, and no gross pathology was found in birds examined 12 weeks after hatching.

Paid claims for mink damage have amounted to 6.2 percent of all paid sonic boom damage claims (Reference 61). In a controlled investigation of the effect of sonic boom on mink (Reference 63), no reaction was found for 2 psf booms. Bell (Reference 61) cites more recent studies which do not contradict this finding. A court decision cited in Reference 61, awarding a mink damage claim, noted that mink in the controlled investigation may have adapted to booms. This further supports the conclusion that even if there is an initial adverse reaction to noise, animals will adapt.

From the above discussion, and noting that all animal harm came at boom overpressures higher than would be tolerated in a residential area, we can conclude that no significant harm should occur to animals at noise levels acceptable to residential communities.

4.2.2 Wildlife

The proposed HIRT site is in a heavily wooded region, which is to be left intact as much as possible. Areas hazardous to humans can be restricted by fencing, but there is no practical way of evacuating wildlife. Since potentially hazardous areas will not be open for recreational purposes, such as hunting, the prime consideration is that the

ecology of the area as a whole not be seriously disturbed. It is assumed that there is nothing exceptional about the local wildlife. If there are any rare or endangered species within a hazardous zone, every effort must be made to evacuate them to a safer area.

Table XI shows expected human reaction to shock waves of various overpressures. These values can be assumed to apply to large mammals, such as deer.

TABLE XI

EXPECTED HUMAN REACTION TO SHOCK WAVES

Overpressure	Expected Reaction
20-144 psf	No injury, temporary hearing impairment lasting several hours (References 64, 65)
720 psf	Threshold for eardrum rupture (Reference 60)
2160 psf	Threshold for lung damage (Reference 60)
2880 psf	Threshold for mortality (Reference 60)

It is not expected that small animals would withstand shock waves as well. Table XII presents data from Reference 60, summarizing overpressures which would cause 1%, 50% and 99% death rates in small animals.

TABLE XII

KILL OVERPRESSURES FOR SMALL ANIMALS

Species	1% Death	50% Death	99% Death
Mouse	1010 psf	1580 psf	2160 psf
Rabbit	1300 psf	1730 psf	2160 psf
Guinea Pig	1440 psf	1870 psf	2440 psf
Rat	1440 psf	2020 psf	2590 psf

In a rather severe laboratory test, guinea pigs were subjected to 1000 sonic booms at one second intervals (Reference 59). Sound pressure levels were 130 dB (1.41 psf). Although autopsy revealed damage to the cochleae, there was no functional impairment of hearing.

A guideline for the sensitivity of birds and bird eggs to blast may be based on the catastrophic mass hatching failure of Dry Tortugas Sooty Terns in 1969 (Reference 66). 99% of the Sooties failed to hatch their eggs. After careful consideration of all possible factors, it was concluded that the most probable cause was low level supersonic flights on two days which generated overpressures of over 100 psf at a critical time of incubation. The Sooties themselves appeared to be unharmed, and the 1970 hatch appears to be normal.

The following table summarizes expected maiming of animals by various shock wave overpressures:

TABLE XIII

SUMMARY OF EXPECTED ANIMAL INJURIES

Overpressure	Reaction
2 psf	No harm
20-144 psf	Temporary hearing impairment Long term exposure leads to permanent hearing impairment
100 psf	Damage to bird eggs; possible total hatch failures
600 psf	Threshold for eardrum rupture in dogs (Reference 60)
1010 psf	Threshold of death for small animals

From Table XIII and the discussion of domestic animals, we may conclude the following:

- Below 20 psf, the only effect on wild animals would be a possible startle reaction.

- Above 20 psf, long term hearing impairment should be expected. How this affects survival of the animals involved depends on how each species depends on hearing for hunting food, predator warning, etc.

- At 100 psf, large-scale failure of bird eggs to hatch should be expected. This will happen for a relatively few noise events if they occur during a critical period of incubation. More research needs to be done to precisely determine this critical period and the threshold overpressure. No physical harm, except for long term hearing impairment, is expected.

- Onset of direct physical harm is expected at 600 psf, with death to small animals beginning at 1000 psf.

The area of each danger zone must be considered, and compared to the total area of the reservation to determine if HIRT noise hazard poses a threat to the ecology of the reservation.

4.3 Buildings and Structures Impact

4.3.1 Factors Affecting Buildings and Structures

In this section the effects of transient pressure pulses and steady state noise on surrounding structures are considered. These structures include typical buildings located in close proximity to the noise sources, and surrounding residential buildings. Basically there are two forms of excitation associated with the HIRT facility which contribute dynamic loadings to surrounding structures. The first of these is the starting shock which can be assumed to load the surrounding structures with a single rectangular pulse. This is followed by the steady state acoustic environment, and during this period the structures are subjected to random pressure fluctuations. These two environments are considered separately in the following discussion since it is assumed that the steady state noise arrives at the surrounding structures at some finite time interval after the structure has responded to the transient pressure pulse.

Structural Response to Transient Loads — When investigating the structural loads imposed by transient pressure pulses such as explosions and sonic boom overpressures, it is convenient to focus attention on the response of simple single-degree of freedom systems. Typical building elements such as windows and walls can usually be idealized into single-degree of freedom systems. In most cases, the transient loads can be approximated by relatively simple pressure pulses without a large number of oscillations such as occur for earthquake loads on buildings. Consequently it is usually possible to neglect the effects of damping on the response of a simple mass-spring system to such loads.

The starting shock produced by the HIRT facility has the form of a rectangular pulse, with a 50 millisecond duration. No published field data are available concerning the response of buildings to this type of transient load. However a considerable amount of field data exists for sonic booms, where the waveform has a characteristic N shape, and blast overpressures, where the waveform is characterized by a triangular pulse having an instantaneous pressure rise. Therefore it is useful at the outset to compare theoretically the way in which simple idealized structures respond to rectangular pulses, sonic booms and blast loadings, before proceeding to analyze existing field data for sonic booms and blasts.

The response of a simple single-degree of freedom system to a transient pulse is characterized by two distinct phases. Initially the system exhibits a forced response with a duration equal to the length of the pulse. This is followed by the residual response phase during which the system performs free vibrations at its natural frequency. The combined envelope of the maximum response amplitudes of the simple system during both the forced and free vibration phases is defined as the "shock spectrum". This envelope, normalized by the static response, x_s, (i.e., the response to a static load having a peak value equal to the magnitude of the pulse) is illustrated in Figure 20 for three different types of transient pulse. Figure 20 illustrates the normalized shock

spectra for an undamped single-degree of freedom system subjected to a rectangular pulse, a triangular pulse and an idealized sonic boom N wave. The ratia of peak dynamic displacement to static displacement, usually defined as the dynamic amplification factor, DAF, is plotted against the parameter $f_0 T$ where f_0 is the resonant frequency of the single degree of freedom system and T is the duration of the positive phase of the transient pulse.

The detailed procedure for constructing the shock spectrum is illustrated in Figure 21 for the case of an idealized sonic boom N wave. There are basically three curves describing the DAF versus $f_0 T$ superimposed in Figure 21; these are the maximum positive forced response x_{max}, the minimum forced response (i.e., negative peak) x_{min}, and the maximum residual response x_r. It can be seen that the envelope to these three curves defines the shock spectrum for a sonic boom N wave, as shown in Figure 20.

It is immediately apparent from Figure 20 that a sonic boom N wave of duration T is frequency selective in terms of exciting an arbitrary structure, whereas the rectangular pulse is not. For example at a value of $f_0 T$ equal to 0.7 the DAF for the sonic boom is about 1.4 whereas for the rectangular pulse the DAF is equal to 2.0. The characteristics of the shock spectra therefore suggest that the single rectangular pulse represents a more severe loading than the sonic boom N wave, since this type of pulse is not selective in terms of coupling with a given structural mode. However, for values of $f_0 T$ in the vicinity of 0.4 to 0.5 the sonic boom N wave is slightly more severe than the rectangular pulse.

The preceding discussion has been concerned solely with a comparison between displacement shock spectra for sonic booms, blast overpressures and a rectangular pulse characteristic of the starting shock from the HIRT facility. This has been done simply because of the fact that most of the available structural response and damage data have been collected during sonic boom studies. Based upon the above comparisons, it is anticipated therefore that damage data collected during sonic boom programs will represent a valid starting point from which an evaluation of the effects of the starting shock from the HIRT facility can be carried out.

Structural Damage Resulting from Transient Loads — It is not normally necessary to consider a shock wave such as a sonic boom as a source of significant design loads on primary load-carrying members of industrial-type structures. However considerable damage to secondary-type structures may result. Sonic boom studies have shown that this secondary type of damage will usually include the following:

- Shattering of glass panes
- Dislodging of curtain wall panels and various components of built-up roofing

- Permanent distortion of doorways
- Extensive cracking of plaster

The foregoing list illustrates the potential damage to structural elements, particularly those of a brittle nature, resulting from transient overpressures. Because of the less stringent design requirements for lateral loads on residential walls, and the corresponding methods of construction, this type of structure is more susceptible to damage from sonic booms. Minimum wind design requirements generally exceed 10 lb/ft^2 corresponding to a nominal 55 mile per hour wind (Reference 67). This suggests that major damage resulting from transient loads would not normally be expected in a residential building which is in good repair. However, the type of wood frame construction which is so widely used for residences is susceptible to deterioration over a long period due to factors such as foundation setting, swelling or warping due to humidity changes and frame distortion due to changing temperature. Thus it is to be expected that there will be a certain percentage of residences in such a condition that any significant dynamic load would be sufficient to cause at least minor damage. Based upon experience reported by Mayes and Edge (Reference 68) for the U.S. Air Force, an evaluation of 3,000 complaints showed that the most common type of damage claimed to be caused by sonic booms was as follows:

- Plaster cracks - 40%
- Broken windows - 30%
- Masonry Cracks - 15%
- Broken tile and mirrors - 8%
- Broken bric-a-brac - 5%
- Damaged appliances - 2%

The failure of windows caused by transient loads represents the most critical form of probable damage. Glass is a brittle material with a yield strength almost equal to its ultimate strength. The breaking strength, commonly used to identify the failure stress of glass, varies over a range from about 3000 psi to 30,000 psi depending upon the type of glass, age, surface condition, built-in pre-stress, and load duration. One of the most important features of glass breaking strength is that for a given load intensity, glass will tend to break at a lower stress for longer duration loads. The "fastest mile" wind loads (i.e., the steady dynamic pressure for the average wind velocity over a one minute period) generally represent the design condition for large windows.

One of the most significant problem areas in attempting to predict glass behavior under dynamic loading is the statistical nature of glass breakage. Even under ideal laboratory conditions, a range of test specimens will exhibit significant standard deviation from a mean breaking stress. In practice the glass will usually fail at a lower breaking stress than that determined in the laboratory because of stress concentrations in the window frames and local surface defects. In fact the location and

number of surface defects is usually the controlling factor which limits the breaking strength of windows.

Because of the uncertainties involved in predicting damage resulting from transient loads, any assessment of probable damage and attempts to prescribe safe limits must necessarily be based upon previous statistical studies. Some field data are available from previous sonic boom and blast studies. In Section 4.3.2, the results of these field studies will be discussed, and suggested limits for free-field overpressures will be introduced.

Structural Response to Steady State Acoustic Loads — A structural element excited by broad-band random pressure fluctuations will theoretically respond in all of its normal modes. That is, the response spectrum will be characterized by peaks associated with the response of the fundamental mode together with the responses of many higher order modes. The acoustic environment produced by the HIRT facility can be considered to be broad band with a peak occurring at about 125 Hz. At large distances from the noise source, the characteristics of this acoustic environment will essentially lie between a plane wave environment and a reverberant environment. The reverberant acoustic field tends to excite many structural modes whereas the plane wave environment tends to be more selective in terms of wavelength coupling. The acoustic environment will excite external building structure and the resulting vibrations will be transmitted to the interior of the building via two paths, the air path and any mechanical paths. Thus, objects within the building will be excited by the internal acoustic field transmitted via the air path, and in addition will receive vibrational energy transmitted from the building walls via mechanical paths.

It is extremely difficult to generalize the effects of acoustic loading on structural members because the response of a given structure depends upon its stiffness, mass per unit area, resonant frequencies and the strength of the coupling between the acoustic field and each structural mode. Attempts to collapse space vehicle structural response data by using mass per unit area and frequency times diameter as normalizing parameters have been reported by Franken (Reference 69) and White (Reference 70). The final results however, have not been entirely satisfactory, due to the omission of bending stiffness in the normalization, and as a result it is usually necessary to investigate each structure separately, using either modal analysis techniques (Reference 70) or statistical energy techniques (Reference 71). The response of typical industrial buildings and residential structure to acoustic loads has received much less attention than space vehicle structure in the past, and again each structure would require individual analysis to determine its behavior under acoustic loading. The results of one experimental study concerning building response, reported by Sutherland (Reference 72), are shown in Figures 22 and 23. These figures describe the variation of acoustic mobility (i.e., acceleration response times surface weight divided by sound pressure) with the frequency ratio $f/f_{1,1}$ for various types of building walls. The modal character of the building response is illustrated by the peaks in each acoustic mobility spectrum.

As an alternative to performing a detailed response analysis for each building however, a good approximation to the peak stress generated by the fundamental mode can be obtained simply by idealizing structural and building elements to flat homogeneous rectangular panels. By considering the fundamental mode of a rectangular panel excited by normal incidence plane waves, a worst case stress condition can thus be investigated. The procedure for estimating the maximum stress in the fundamental mode of a rectangular panel has been described in detail by Sutherland (Reference 72). Briefly, it can be shown from these results that the peak stress in the fundamental mode can be estimated from the following relation:

$$\sigma_{max} = \frac{36.75\,\beta E h}{a^2 f_0^{1.5}} \left[\frac{W_a(f)_{max}}{Q_0} \right]^{\frac{1}{2}} \quad \text{lb/in}^2$$

where

β	=	Constant depending upon panel aspect ratio b/a (see Table XIV below)
E	=	Youngs Modulus of Elasticity lb/in.^{2}
h	=	Panel thickness, in.
a	=	smallest panel dimension
f_0	=	resonant frequency of the fundamental panel mode (the 1, 1 mode)
Q_0	=	Dynamic amplification factor for the fundamental mode ($\doteqdot 1/2\delta$)
δ	=	Damping ratio
$W_a(f)_{max}$	=	Maximum acceleration power spectral density in g^2/Hz

TABLE XIV. VALUE OF CONSTANT β FOR USE IN ESTIMATING MAXIMUM STRESS IN THE FUNDAMENTAL MODE OF A RECTANGULAR PANEL

Panel Aspect Ratio b/a	1.0	2.0	5.0
β	7.05	5.83	5.49

The maximum acceleration power spectral density, $W_a(f)_{max}$ is determined from Table XV which defines values of the acoustic mobility

$$\left[\frac{W_a(f)\, w^2}{W_p(f)\, Q_0^2} \right]^{\frac{1}{2}}_{max} \qquad \text{in g's ,}$$

for various boundary conditions. The other parameters involved in the above dimensionless expression for acoustic mobility are defined as follows:

w = surface weight density lb/in.^{2}

$W_p(f)$ = pressure power spectral density (psi)^2/Hz

TABLE XV. NUMERICAL VALUES OF MAXIMUM ACOUSTIC MOBILITY IN THE FUNDAMENTAL MODE FOR UNIFORM PANELS SUBJECTED TO NORMALLY INCIDENT PLANE WAVES

Boundary Conditions Along Short Edges	Boundary Conditions Along Long Edges			
	SS	SC	CC	CF
FF	1.27	1.30	1.33	1.45
SS	1.62	1.65	1.69	1.85
SC		1.68	1.72	1.89
CC			1.75	1.92
CF				2.11

F = Free edge;

S = Simple support or pinned edge

C = Clamped or fixed edge

Thus by using the above simple approximation for a panel subjected to normally incident acoustic waves, the peak stress σ_{max} may be computed for any arbitrary sound pressure level.

In order to define the acoustic field which is set up within a particular building, it is necessary to compute the noise reduction and then to subtract this from the external acoustic field. The noise reduction through a typical building or structure can be computed from the following relation:

$$N.R. \quad = \quad TL - 10 \log_{10} \left(\frac{S_t}{\overline{\alpha} \, \overline{S}} \right) - \text{dB}$$

where

$TL \quad = \quad$ Transmission Loss - dB

$S_t \quad = \quad \Sigma \, S_j$, the total transmitting surface area

$\overline{\alpha} \quad = \quad \left(\Sigma \, \alpha_i \, S_i \right) \Big/ \left(\Sigma \, S_i \right)$, the average absorption coefficient

$\overline{S} \quad = \quad \Sigma \, S_i$, the total absorbing surface area

$\alpha_i \quad = \quad$ absorption coefficient associated with area S_i

Alternatively, if the average transmission loss and an average internal absorption coefficient, $\overline{\alpha}$, are known for each frequency bandwidth, then the curves shown in Figure 24 may be used to determine the average Noise Reduction for that particular bandwidth. Typically, values of $\overline{\alpha}$ will range from $\overline{\alpha} = 0.05$ for a "live" room, $\overline{\alpha} = 0.15$ for an "average" room, to $\overline{\alpha} = 0.4$ for a "dead" room (Reference 73).

To estimate the transmission loss of a simple wall or panel, the design chart shown in Figure 25, based on Beranek's results (Reference 73), may be utilized. For a given structure the following procedure should be adopted in estimating the transmission loss:

- compute the surface density of the structure w (lb/ft^2) and for any typical frequency determine the field incidence TL from Figure 25. This establishes point B shown in the sketch inset in Figure 25.

- construct a line of 6 dB per octave slope through point B up to a frequency of approximately $0.3 \, f_c$ where f_c is the acoustic critical frequency given by:

$$f_c = \frac{c^2}{2\pi} \sqrt{\frac{w}{Dg}}$$

where

c = speed of sound (ft/sec)

D = bending stiffness (lb ft)

g = gravitational acceleration (ft/sec^2)

This establishes the line AC.

- construct a horizontal line through C to D where the latter point is positioned at the critical frequency f_c
- above point D construct a line, having a slope of approximately 10 dB per octave, to point E.
- this transmission loss can then be converted to noise reduction of the particular building enclosure by use of the equation given on the previous page.

Alternatively the transmission loss may be estimated directly from the design curves from Reference 72 shown in Figure 26 for typical building elements.

Structural Damage Resulting from Acoustic Loads — The most common form of damage resulting from acoustic loads is fatigue damage which occurs after some finite number of vibration cycles. A considerable number of acoustic fatigue studies have been reported for aerospace-type structural materials. In the majority of cases, the test specimens consisted of rivetted aircraft-type panels subjected to both broad-band and narrow-band pressure fluctuations. However, very few studies have been reported concerning building damage resulting from acoustic loads. During one study, reported by Sutherland, et al. (Reference 72), the damage to typical industrial and residential structure resulting from broad-band noise was investigated. Their damage data for an eight-inch concrete wall, a corrugated steel wall, and typical residential walls and roof are summarized in Figure 27. These results were obtained during testing in a reverberation room and the specimens were subjected to broad-band (20 Hz-3000 Hz) random noise. The test specimens consisted of the following;

- 20 ft x 18 ft x 26 gauge corrugated steel walls having surface weights between 1.59 and 1.8 lb/ft^2
- An 8-inch concrete block wall having a surface weight of 40 lb/ft^2

- An 8 ft by 10 ft section of a standard wood frame wall with a surface weight of 8.5 lb/ft^2

- An 8 ft by 10 ft section of insulated wood frame wall having a surface density of 8.5 lb/ft^2

- A 14 ft by 10 ft section of a wood frame roof having a surface density of 8.5 lb/ft^2

It can be observed from Figure 27 that for overall sound pressure levels in excess of 140 dB, significant structural damage to these test specimens began after a very short time, typically on the order of ten minutes. Unfortunately these results are insufficient to estimate the probable time to failure for lower sound pressure levels in the region of 120-130 dB. However, they serve to illustrate the damaging effects of acoustic loads on building-type structures. Damage caused by acoustic loading will generally include the following:

- glass breakage
- plaster cracking and crumbling
- masonry cracking and crumbling
- fatigue cracks in metal sheeting particularly around rivet holes
- dislodging of structural elements and objects

Suggested limits for acoustic loads applied to building-type structures will be discussed in greater detail in Section 4.3.2.

4.3.2 Specification of Limits for Buildings and Structures

In this section the definition of safe limits for structural loads imposed by transient pressure pulses and broad-band noise are considered. The two principal forms of excitation associated with the HIRT facility are again considered separately. Safe limits for transient overpressures are discussed first, followed by a discussion of safe limits for steady-state noise.

Limits for Transient Pressure Pulses — A significant amount of damage data has been obtained during previous sonic boom studies, and is considered to be applicable as a starting point in attempting to prescribe limits for rectangular pressure pulses. These previous studies include the Nellis Air Force Base tests and the White Sands Missile Range tests (References 64, 74 and 75), together with various accidental sonic boom overflights (Reference 76). A general review of damage claims associated with sonic boom overpressures caused by both operations and accidents, is summarized in the table on the following page. This table defines the average free-field overpressure, the total number of claims and a breakdown of claims by damage category.

TABLE XVI

CLAIMS DATA FROM CERTAIN DOCUMENTED STUDIES (REFERENCE 76)

Overflight Locations	Average Free-Field Overpressure lb/ft^2	Total No. Claims	Glass (% of Total)	Wallboard and Plaster (% of Total)	Bric-a-Brac (% of Total)	Structural and Other (% of Total)	Damage Claims Per Million Population
Engineer Investigators:							
Oklahoma City	1.2	4901	12	56	2	30	6.78
St. Louis '61	1.8	157	30	49	6	15	3.64
Average	--	--	21	53	4	23	--
Air Force Investigators:							
Chicago	1.8	3156	--	--	--	--	13.0
Milwaukee	1.8	639	28	42	7	23	6.67
Pittsburgh	1.8	1125	43	25	6	26	14.8
St. Louis '61	1.8	1624	35	34	12	19	5.10
St. Louis '65	1.8	491	27	46	5	22	12.9
Average	--	--	29	42	6	23	--
Sonic Boom Accidents:							
Cedar City	17	97	80	13	1	6	43,700
Wash. Ct. Hse.	22	198	78	--	--	--	16,500
Panama City	15	122	66	16	9	9	427
Boston	5	18	56	6	22	16	333
Average	--	--	68	10	10	10	--

The most striking feature of these results is that even at low overpressures, in the region of 1.2 lb/ft^2, a substantial number of damage claims have been documented. The results shown in the foregoing table are unusual in the sense that wallboard and plaster damage represents between 25 and 56 percent of the total claims for low overpressures, while this type of damage appears to decrease to between 6 and 16 percent of the total claims for the higher overpressures. In the last column, the total number of damage claims per million population is listed for each particular overflight. It is not known whether the whole community or only the affected section of the community have been considered in developing these figures. It is also emphasized that the data in the table have been collected from isolated incidents involving single sonic boom overflights, except for the Oklahoma City data which are based upon 1253 sonic booms having an average strength of 1.2 lb/ft^2. These figures do not therefore include the effects of cumulative damage. During controlled tests at White Sands Missile Range (References 74 and 75) a cumulative damage study was conducted on seven test structures, and it was determined that a cumulative damage threshold was a real possibility. Wiggins (Reference 76) has analyzed this data and as a result suggested that under 2 lb/ft^2 sonic booms, 19 structures per million could be expected to suffer cumulative damage. However, during repetitive boom tests on glass panels utilizing Wyle Laboratories Sonic Boom Simulator, White (Reference 77) found that for overpressure levels below 10 lb/ft^2, cumulative damage effects were insignificant.

Based upon available sonic boom data, Wiggins (Reference 76) has plotted glass damage as a function of overpressure, as shown in Figure 28. Two regression lines have been plotted by Wiggins, one based upon the assumption that each data point is of equal weight, while the other weights each data point with regard to its uncertainty. The data shown in Figure 28 are insufficient to determine whether or not the curve changes slope at low overpressures in the same manner as fatigue data. It should also be noted that for overpressures less than about 20 lb/ft^2 very limited data are available, in fact only data from accidental overpressures. Although the magnitudes of the overpressures resulting from the accidental overflights and the Medina explosion have been estimated, the results appear to correlate with the data obtained from the controlled experiments at White Sands and Nellis Air Force Base. Due to the lack of data, confidence in the damage prediction for average overpressures below 3 lb/ft^2 is consequently rather limited. From Figure 28 it is observed that an overpressure of 2 lb/ft^2 results in a predicted damage rate of 9×10^{-10} broken panes per boom-pane exposure from the weighted curve, and about 1×10^{-8} broken panes per boom-pane exposure from the non-weighted curve. Boom-pane exposure is defined as the product of the number of booms and the number of panes exposed to a boom of given strength.

As a result of these studies, Wiggins (Reference 76) has proposed the damage prediction chart shown in Figure 29, which describes the maximum safe free-field overpressure versus glass pane area for a range of glass thicknesses. In deriving this chart it was assumed that; the coefficient of variation of the peak overpressure was 33%, the dynamic amplification factor was equal to 2, and stress raisers in the window frame reduced glass strength by a factor of 2.

In summary, the damage prediction chart described in Figure 29 and the damage claims data presented in the table appear to represent the state of the art in terms of assessing the effects of transient pressure pulses on surrounding structure. It is emphasized that both Figure 29 and the table have been compiled using sonic boom data whereas the rectangular pressure pulse, which is of principal concern in this discussion, has been shown to be slightly more severe than the sonic boom N wave. However, it is considered that an adequate margin of safety is inherent in the damage prediction chart shown in Figure 29. Thus the damage prediction chart should provide a realistic basis for evaluating the effects of a rectangular pressure pulse on surrounding buildings and structures.

Limits for Acoustic Loads — In Section 4.3.1 the difficulties associated with defining maximum permissable sound pressure levels for given structural elements was discussed. It was emphasized that for building-type structures, the responses to acoustic loading must generally be computed individually, since many structural parameters interact to affect the final response spectrum. Fatigue damage data for building elements were also reviewed, and it was concluded that insufficient data were available for the purposes of predicting limiting sound pressure levels. However, a technique involving estimation of the maximum stress in the fundamental mode of idealized rectangular panels was suggested as a means of obtaining a worst case design condition. This technique is relatively straightforward and, for a given structure, the ratio of peak stress to sound pressure level can be obtained with a minimum of effort.

A similar technique was uitlized by Sutherland (Reference 72) to develop acoustic criteria for typical building structure. Based upon the work reported in Reference 72, acoustic criteria have been developed for typical wall and window structure, and are summarized in Figure 30. This figure defines critical one-third octave band sound pressure levels for various types of wall construction and window glass thicknesses. These criteria are based upon those developed by Sutherland (Reference 72) for excitation at the fundamental resonance of the wall. However, to account for broad—band excitation of wall structures, the maximum levels have been limited accordingly. In setting these maximum levels, previous acoustic fatigue studies on building and window glass panels (References 72 and 78) were taken into account. In addition the following assumptions have been made;

- all panels were assumed to be simply-supported
- panel aspect ratios were assumed to be 3:1 , which represents a worst case design condition
- a stress concentration factor 2.5 was assumed
- a safety factor of 2.0 on the maximum stress was incorporated

Acoustic criteria for laboratory equipment malfunction have also been presented by Sutherland (Reference 72), based upon acoustic test data reported in References 79 and 80. A partial listing of this data is shown in Table XVII.

TABLE XVII

ACOUSTIC TEST LEVELS FOR EQUIPMENT MALFUNCTION

CLASS	ACOUSTIC TEST LEVEL*
Electrical and Electronic Components	Minimum Failed dB
Amplifier, Decade, Lab. Type	120
Coaxial Cable	138
Commutators	142
Computer, Analog	165
Current Repeater	134
Oscillator, Lab. Type	135
Oscilloscope, Lab. Type	130
Potentiometer	138
Recorder, Strip Chart	139
Rectifier	130
Relays	131
Relay Module, Solid State	156
Resistance to Current Convertor	139
Switch, Solenoid	128
Switch, Fluid Pressure, Electrical	142
Thermal Sensors	134
Transmitter, Telemetry	140
Vacuum Tubes	110
Voltage Regulatorl	130
Voltage to Current Convertor	160
Voltmeter, Lab. Type	130
Pneumatic and Hydraulic Components	Minimum Failed dB
Controller, Pressure	134
Indicating Switch, Pressure	159
Switch, Pressure Activated	135
Transmitter, Pressure	134
, Temperature	160
Valve, Solenoid	163

* Octave Band Sound Level in dB re: 0002 microbars from 200-2000 Hz
Minimum at which malfunction occurred

The foregoing table defines the minimum octave band sound pressure level in the frequency range of 200-2000 Hz for which a malfunction occurred. A malfunction is defined as any momentary out-of-tolerance performance of the equipment, such as excessive noise, contact chatter, etc. Except for the case of Vacuum Tubes, the damage to equipment from acoustic loads is not generally irreversible. A more complete tabulation of equipment test levels, which includes those maximum octave band levels for which equipment showed no malfunction, can be found in Reference 72. From Table XVII, it may be concluded that the maximum permissible octave band sound pressure level over the range of 200-2000 Hz would be 110 dB (or 105 dB in any one-third octave band). Octave band levels in excess of this would be expected to cause equipment malfunction.

5.0 ASSESSMENT OF ENVIRONMENTAL IMPACT OF HIRT NOISE

This section presents a general assessment of the environmental impact of HIRT noise. Included in this assessment are people living and working in the vicinity of AEDC, domestic animals and wildlife which may be exposed to HIRT noise, and buildings and residential type structures which may be affected by the HIRT noise. This assessment is made by comparing the limits for acceptable noise environments, which were derived independent of actual HIRT noise levels, with the noise environments produced by the HIRT facility. From this assessment, potential problem areas are readily identified together with those observers which will be within safe and acceptable limits during HIRT operation.

5.1 Human Impact

Human impact of any given sound for a single event is best measured by its perceived noise level. Community impact of a series of noises is measured by the Noise Exposure Forecast. Since NEF is an average of noise events over a period of time, the operating schedule of HIRT must be taken into account. To compare the noise environment of HIRT to the human impact limits derived in Section 4.1, the following are required:

1) Perceived noise level of the starting shock and steady noise for a single run, as a function of run conditions.

2) Noise Exposure Forecast as a function of run conditions and frequency of runs.

3) Statistical analysis of expected HIRT utilization, to determine average run conditions and frequency, so that average NEF can be found.

These are calculated in subsections 5.1.1 through 5.1.3. With these in hand, an assessment is presented in subsections 5.1.4 through 5.1.6 for each type of observer for which a limit has been established. This assessment includes all personnel who may be affected by the environmental impact of HIRT noise.

5.1.1 Perceived Noise Levels

Starting-Shock Environment — The equivalent perceived noise level of the starting shock wave may be calculated from the overpressure presented in Section 3.1.1, using the correlation developed in Section 4.1.1. The correlation depends only on shock overpressure, which is the same for all ground cover and atmospheric conditions. Figure 31 shows equivalent PNdB versus r at maximum mass flux.

Steady-State Exhaust Flow Environment — Perceived noise levels, as described in Section 4.1.1, have been calculated from the spectra and overall sound pressure levels presented in Sections 3.2.2 and 3.2.3. Figure 32 shows PNdB at maximum mass flux

versus r for radial spreading, clear terrain and winter and summer ground cover.

Perceived Noise of Combined Starting Shock and Steady-State Exhaust Flow Environment — Following the principle of equal noisiness for equal acoustic energy, the perceived noise level of the combined starting wave and steady noise is found by adding the perceived noisiness of each on an energy basis:

$$PNL_{total} = 10 \log_{10} \left(10^{\frac{PNL_{steady}}{10}} + 10^{\frac{PNL_{shock}}{10}} \right)$$

Note that when one of the two PNL's is much larger than the other, the total PNL is approximately equal to that one. When $PNL_{steady} = PNL_{shock} = PNL$, then $PNL_{total} = PNL + 3$. Figure 33 shows the perceived noise level for the combined noise environment versus distance.

The NEF rating is based on EPN, equivalent perceived noise level, defined as

$$EPN = PNL + 10 \log \frac{t}{15 \text{ sec}}$$

where t = duration of the noise. For HIRT, the noise lasts approximately 3 seconds; this gives:

$$EPN = PNL - 7$$

5.1.2 NEF as a Function of PNL_{max} and Schedule Parameters

The noise exposure forecast for N runs at conditions i is defined as:

$$NEF_i = EPN_i + 10 \log_{10} \frac{N_i}{K} - 75 \tag{8}$$

where K = 1.2 at night and 20 during the day, with day defined as 0700 to 2200. The overall NEF is obtained by summing the NEF_i on an energy basis:

$$NEF = 10 \log_{10} \sum_i 10^{\frac{NEF_i}{10}} \tag{9}$$

The acoustic output of HIRT scales simply with mass flux, so that sound pressure level at mass flux $\dot{m}$ is related to sound pressure level at $\dot{m}_{max} = 165{,}000\ lb_m/sec$ by:

$$SPL = SPL_{max} + 20 \log_{10} \frac{\dot{m}}{\dot{m}_{max}} \tag{10}$$

The spectrum remains essentially unchanged as $\dot{m}$ varies, so that perceived noise level and equivalent perceived noise level scale in the same manner. Thus:

$$EPN_i = EPN_{max} + 10 \log_{10} \left(\frac{\dot{m}_i}{\dot{m}_{max}} \right)^2$$

$$= PNL_{max} - 7 + 10 \log_{10} \left(\frac{\dot{m}_i}{\dot{m}_{max}} \right)^2 \tag{11}$$

If Equation (11) is substituted into Equation (8) and thence into Equation (9), we obtain, after slight manipulation,

$$NEF = PNL_{max} - 82 + 10 \log_{10} \sum_i \frac{N_i}{K} \left(\frac{\dot{m}_i}{\dot{m}_{max}} \right)^2 \tag{12}$$

The noise exposure forecast can thus be obtained from the perceived noise at maximum mass flux, Figure 33, and a term which we may call the "frequency and intensity factor", FIF. Dividing the runs i into day and night runs,

$$FIF = 10 \log_{10} \left\{ \sum_i \frac{N_{i_{day}}}{20} \left(\frac{\dot{m}_i}{\dot{m}_{max}} \right)^2 + \sum_i \frac{N_{i_{night}}}{1.2} \left(\frac{\dot{m}_i}{\dot{m}_{max}} \right)^2 \right\} \tag{13}$$

All information regarding run schedule and test conditions is accounted for in FIF. Once FIF is determined from Equation (13), NEF is found for any given location by:

$$NEF = PNL_{max} - 82 + FIF \qquad (14)$$

Figure 34 is a chart for the graphical solution of Equation (13). The section at the bottom provides a value of

$$\sum_i \left(\frac{\dot{m}_i}{\dot{m}_{max}} \right)^2 \frac{N_{i_{day}}}{20} \quad ,$$

and the section at the left provides the similar night quantity, given $\dot{m}_i$ and N_i . The central section then gives 10 $\log_{10}$ of the sum, FIF. Shown on Figure 34 is the example of 10 daytime runs at $\dot{m}/\dot{m}_{max} = 0.4$, and 3 night runs at $\dot{m}/\dot{m}_{max} = 0.6$, for which FIF = 0. Figure 35 is a similar chart for $\dot{m}/\dot{m}_{max} \leq 0.5$, over which range Figure 34 is too small to read comfortably.

It should be noted that Figures 34 and 35 can be used to graphically calculate FIF for mixtures of runs.

5.1.3 Noise Exposure Forecast for Projected HIRT Usage

The two parameters N and $\dot{m}/\dot{m}_{max}$ are not unrelated. Runs at higher $\dot{m}$ will be less frequent due to increased pumping time required for each run. Figure 36 shows expected run frequency capability as a function of $\dot{m}$ (Reference.81). Taking the most probable operation curve in Figure 36, N is specified by $\dot{m}$, so that FIF is a function of $\dot{m}$. Figure 37 shows FIF as a function of $\dot{m}$, assuming a full 24 hour schedule. FIF ranges from a maximum of 9.1 at $\dot{m}$ = 135,000 lb/sec to less than -10 at mass fluxes below 10,000 lb/sec.

From Figure 37, it is clear that FIF is highly dependent on mass flux. Figure 38 is the projected utilization of HIRT, showing the percent of runs expected to fall within several operating zones (Reference 81). Stagnation pressure is not important for noise. The distribution shown in Figure 38 as a function of p_0 and $\dot{m}$ has therefore been collapsed into a distribution as a function of $\dot{m}$ only, Figure 39. In obtaining the distribution of Figure 39, it was assumed that runs in each zone of Figure 38 are uniformly distributed over $\dot{m}$, e.g., runs in the zone marked "35%" are assumed uniformly distributed over the range $\dot{m}$ = 28,000 lb_m/sec to 72,000 lb_m/sec, so that the contribution of this zone is 35/(72-28). The distribution in Figure 39 is percent per $\Delta\dot{m}$ = 1,000 lb_m/sec , so that the value at $\dot{m}$ is approximately the percentage of

runs lying between $\dot{m}$ and $\dot{m}$ + 1000 lb_m/sec . The step nature and irregularity of Figure 39 reflects the simple method used to calculate it.

Figure 40 is the first integral of Figure 39, and is more useful in describing the run distribution. The median operating condition is at the 50% point, for which $\dot{m}$ = 55,000 lb_m/sec . Half the runs fall in the range 35,000 lb_m/sec to 75,000 lb_m/sec .

Using the relation between $\dot{m}$ and FIF , Figure 37, the distribution versus $\dot{m}$ of Figure 40 has been converted to distribution versus FIF. Figure 41 shows the integrated distribution; the percent distribution per $\dot{m}$ is indicated in the figure (not to scale). The 50% point occurs at FIF = 4. The range of FIF is -16 to +9 , with 80% of runs having FIF between -3 and +8.

Figure 42 shows NEF as a function of FIF and PNL. It is a graphical representation of:

$$\text{NEF} = \text{PNL} - 82 + \text{FIF} \qquad (15)$$

Indicated are the median and range of FIF. Several of the human impact limits determined in Section 4.1.3 are indicated.

5.1.4 Community Reaction

Figure 43 shows the noise exposure forecast for the combined noise environment at average test conditions, NEF = 4. The four curves represent no attenuation, air absorption at 50% humidity, air absorption and winter ground cover attenuation, and air absorption and summer ground cover attenuation.

Shown in Figure 43 are the limits NEF = 5 for hospital zones, and NEF = 10 to 20 for residential communities. To help examine the noise impact, Figure 44 is a map of the area surrounding AEDC, overlayed with contours of constant radius from HIRT.

The NEF values for the three possible ground cover conditions — clear terrain, winter ground cover, and summer ground cover — are indicated. The following is a summary of distances marking NEF = 5, 10, 20 and 40:

	NEF	Summer Vegetation	Winter Vegetation	Clear Terrain
Hospital Limit	5	4.8 miles	5.7 miles	13.7 miles
Residential Limit	10	3.6 miles	4.3 miles	10.4 miles
	20	2.1 miles	2.5 miles	6.0 miles
Unsuitable for Residential Use	40	0.83 miles	1.0 miles	1.7 miles

The zone NEF ≥40 is not suitable for residential use due to long term health hazard. Depending on ground cover, this zone may extend out to 1.7 miles (cleared terrain). Except for a small area to the east of the reservation approximately 1.2 miles from HIRT, this area is within the AEDC reservation and will not contain residences. The importance of retaining ground vegetation for areas surrounding HIRT is evident. Assuming that present ground cover is retained, the NEF = 40 impact boundary is contained to within one mile of HIRT which is within the present AEDC reservation.

In the zone 20 ≤ NEF ≤ 40 there is little health hazard; however, annoyance could be a real and serious problem. Nighttime operation will awaken a significant fraction of the population and daytime operation will disrupt many normal daytime activities. For winter vegetation, this zone extends out to 2.5 miles from HIRT which is beyond the AEDC reservation boundary to the east. Fortunately, this area is not a residential area although Interstate 24 does pass within this boundary. A discussion of the noise impact on passing motorists is presented later in this section.

The zone 10 ≤ NEF ≤ 20, the proposed limits for residential use, represents the onset of community annoyance. Below NEF = 10, there should be very few incidents of genuine annoyance. The boundary for NEF = 10 is 4.3 miles from HIRT. A few rural houses may be exposed to NEF values approaching 20; however, these residences will be surveyed prior to and during HIRT shake-down tests to determine actual annoyance levels.

The limiting zone for hospitals is NEF = 5, and for winter ground cover extends out to 5.7 miles from HIRT. Exceeding the hospital limit can have serious consequences. It applies to any hospital which has patients recovering from serious illnesses where rest and sleep are necessary. Nursing homes must be included in this group since patients are generally elderly and are not necessarily in good health. It is noted in Section 4.1.3 that old people are more sensitive to sleep disturbance than the average population.

The question of community noise is most important in heavily populated areas. The three nearest communities to AEDC are Hillsboro, Manchester and Tullahoma. The populations, distances, and predicted noise levels for these three communities are tabulated below:

			NEF	
	Population	Distance	Summer	Winter
Hillsboro	200	4.0 miles	8	12
Manchester	6,125	6.5 miles	1	3
Tunnahoma	15,507	9.5 miles	-4	-3

Residential limits as recommended are met for all three communities with a reasonable margin for Manchester and Tullahoma. The hospital limit is not met for Hillsboro; however, this community does not have hospital facilities.

The nearest hospital is located southeast of Manchester at a distance of 5.8 miles from HIRT. This location is almost exactly on the NEF = 5 boundary and represents a potential problem area. During facility shake-down tests, noise at the hospital will be monitored to determine actual noise levels particularly inside typical rooms housing patients.

A special point of concern is the Interstate Highway, I-24, passing within 2 miles of HIRT. Generally, passing motorists will be exposed to single noise events; however, they will not be warned prior to exposure. They may be analyzed as unwarned outdoor observers exposed to single event noise levels. The limit for this catagory personnel has been established (for AEDC workers) at 115 PNdB perceived noise level. Figure 33 shows single event perceived noise levels for maximum mass flow rate conditions; Figure 45 shows this for average mass flux. The values at the nearest point of I-24 are as follows:

	Cleared Terrain	Winter Vegetation	Summer Vegetation
Average Test Conditions	105	94	89
Most Severe Test Conditions	115	104	99

These noise levels appear to fall within acceptable limits.

It should be noted that typical truck noise can be louder than the 115 PNdB limit proposed above. Other than the fact that HIRT noise will have a different tonal quality, combined with a sudden short duration of exposure, the noise impact to passing motorists should be not worse than that produced by a passing truck. During facility shake-down, a survey of passing motorists exposed to HIRT noise will be conducted to determine any possible startle reactions to the noise.

In summary, residential areas (including I-24 motorists) do not pose any definite serious problems as far as HIRT noise impact is concerned. There are marginal areas of concern which should be monitored during facility shake-down tests. Included among these are:

- Manchester Hospital
- I-24 Motorists
- Miscellaneous Rural Houses

Appropriate measures of noise control will be implemented, as required, to maintain acceptable noise impact levels as discussed in Section 6.0.

.1.5 AEDC Personnel

The noise impact on most workers is governed by NEF rating calculated for daytime runs. These NEF values are approximately 10 lower than those shown in Figure 43 (which include sleep disturbance criteria), and are shown in Figure 46. The limits for various personnel are indicated. Figure 47 is a map of the AEDC complex, with these NEF values indicated on contours. The distances from HIRT at which the noise does not interfere with various work activities are:

Activity	Winter Vegetation	Summer Vegetation
Machine Shops	900 ft	850 ft
Workshops and Laboratories	2,100 ft	1,800 ft
Outdoor Workers	2,900 ft	2,500 ft
Secretarial (Typing)	3,900 ft	3,400 ft
Drafting	5,100 ft	4,400 ft
Executive Offices	8,500 ft	6,900 ft

For the first four categories of workers, NEF limits will generally be met at existing AEDC facilities. However, there is concern for outdoor workers with activities on the HIRT side of 1st Street. This problem is discussed in greater detail in Section 6.0 For certain office workers, particularly executive personnel, annoyance may be anticipated for all the AEDC facilities within the 8,500 foot radius. This includes virtually all the facilities at AEDC. This conclusion suggests that high mass flow runs be conducted during the evenings; however, community annoyance goes up under these conditions. A reasonable trade-off is to limit high pressure runs to the week-end daytime hours. Under these conditions, few office personnel will be at AEDC and residential people will not experience sleep disturbance. Experience with the facility will be required to evaluate, conclusively, the potential annoyance level for AEDC office personnel. It should be noted that the problem is one of annoyance and not potential health hazard. Consequently, the attitudes of AEDC personnel toward the noise may be such that higher NEF limits may be acceptable to them; whereas it would not be acceptable to general office personnel not directly involved in the AEDC operation.

In addition to annoyance, unprotected personnel must not be exposed to single events over 125 PNdB when forewarned, and 115 PNdB when not forewarned. Figure 48 is a map of the facility with noise contours taken from Figure 38, for maximum operating conditions. Figure 49 shows the same information for average running conditions. Assuming favorable wind conditions, so that there will be at least winter ground cover attenuation, these limits occur at the following ranges:

Noise Level	Maximum Mass Flux	Average Mass Flux
125 PNdB	3,500 ft	1,700 ft
115 PNdB	6,000 ft	3,500 ft

Generally, a restricted zone for outdoor personnel in the vicinity of 3,500 ft must be established for periods of maximum mass flux operation. Hearing protection devices must be made available to personnel in this zone. Further, warning systems must be installed for up to 6,000 ft from HIRT, to be activated when run schedule (or unfavorable wind) warrants. Recommendations for various classes of control zones are discussed in Section 6.1.

It should be noted that the sound levels in Figures 33, 45, 48 and 49 do not include local effects due to buildings. Reflection from the sides of buildings facing HIRT can add 3 to 6 dB to free-field noise levels. Acoustic surveys during HIRT shake-down operation will therefore include a survey of building walls facing HIRT, so that hazardous reflection/focal areas can be located and appropriately controlled.

5.1.6 HIRT Personnel

The control room and buildings for HIRT operating personnel are in an environment subject to perceived noise levels of 150 PNdB. Since this is an upper limit for personnel even with ear protection, nobody should be allowed outside the operating building while HIRT is running. (It should also be noted that the tremendous velocities in the exhaust stack are likely to scatter any debris within the stack over the surrounding area. Since debris in the form of birds within the stack is always a possibility, remaining indoors is a reasonable precaution on this count as well.) The degree of soundproofing required for the control building depends on noise level desired inside. A minimum of 25 dB is needed to conform with the Walsh-Healey standards, and is easily attainable with conventional brick and mortar construction. However, since engineering and administrative personnel will be located at the HIRT facility as well, special consideration will be given to the building design to achieve acceptable levels of noise attenuation.

5.2 Animal Impact

Impact on domestic animals is covered by community impact, Section 5.1.4. This section will assess the impact on wildlife.

Physical harm to animals is dependent on the strength of the starting shock wave. Figure 50 shows the overpressure of the starting wave for maximum mass flux for both directly overhead and at ground level. The curve for ground level is somewhat high at small r, since near-field stack shielding has been neglected. The limits discussed in Section 4.2 for injury to animals occur at the following distances:

Overpressure	Effect	Distance	Area Enclosed
2 psf	No reaction	3300 ft	785.00 acres
20 psf	Onset of hearing loss	330 ft	7.85 acres
100 psf	Bird eggs may not hatch	64 ft	---
600 psf	Threshold for eardrum rupture (first physical harm)	11 ft	Inside Exhaust Stack
1010 psf	Threshold of mortality	6.5 ft	

Note that the upper two levels of overpressure occur inside the stack, with overpressures capable of direct harm occurring well within the stack. The overpressure at the stack exit (based on the upper curve of Figure 50) is approximately 100 psf. No physical harm, except, possibly, to eggs at a critical point of incubation, will result outside the stack. The stack exhaust itself, with speeds in excess of 300 ft/sec, will pose much

more of a threat to birds flying overhead than will the sound. The zone in which any type of harm, other than startle reaction, may be expected is within 330 feet. The total area of this zone is 7.85 acres which is approximately 0.026% of the total unimproved area of 30,578 acres for the reservation. The fraction of the animal population involved is not large enough to cause a significant change in the ecology of the area as a whole.

In summary, the impact of HIRT noise on wildlife is sufficiently small to be discarded as a potential problem area. As a protective measure, large mammals will be evacuated from Control Zone 1 (see Section 6.0) to preclude any damage due to startle reactions which these animals may experience.

5.3 Building and Structures Impact

In assessing the impact of the HIRT facility environment upon surrounding structures, it is necessary to consider the following two structural categories:

- AEDC structures which are located in close proximity to the HIRT facility
- Residential structures in the surrounding communities

The AEDC buildings which are closest to the HIRT facility can be identified from Figure 47. They are as follows:

- The model shop building
- The instrument calibration laboratory
- The fire, police and communications building.

These buildings are between 3000 ft and 3500 ft from the HIRT facility. The nearest residential structures likely to be affected are estimated to be approximately 8000 ft from the HIRT facility.

5.3.1 Effects of the Broad-Band Acoustic Environment

The effects of the broad-band acoustic environment can be readily determined with the aid of Figure 51. This figure shows a comparison between the anticipated acoustic levels for the closest AEDC and residental structures and the acoustic criteria for structural damage. The acoustic criteria shown in Figure 51 are those limits specified for single-strength glass in Figure 30. It can be concluded from this figure that damage caused by the broad-band acoustic environment is not expected.

It was stated in Section 4.3.2 that the maximum permissable one-third octave band sound pressure level for laboratory equipment was 105 dB over the range of 200 Hz to 2000 Hz. Assuming a minimum noise reduction of 20 dB in any one-third octave band for the brick-walled instrument calibration laboratory, this would mean that an external sound pressure level of 125 dB in any one of these third-octave bands would be required to cause damage. Since the maximum one-third octave band sound pressure level for this location is about 112 dB (see Figure 51) it can therefore be concluded that damage to laboratory equipment within the calibration laboratory is not expected.

5.3.2 Effects of the Starting Shock Environment

It is clear from the discussion in the preceding sections that glass breakage represents the most critical form of damage resulting from transient pressure pulses. The damage prediction chart shown in Figure 29 can be utilized to derive glass breakage criteria for single-strength glass, double-strength glass and plate glass. Based upon Figure 29, the following glass breakage criteria may be defined as acceptable limits:

PANE AREA ft^2	MAXIMUM SAFE FREE-FIELD OVERPRESSURE lb/ft^2		
	Single-Strength Glass	Double-Strength Glass	1/4-Inch Plate Glass
4	9.0	13.0	38.0
6	7.5	11.0	29.0
10	5.5	8.0	19.0
20	2.9	4.5	10.0
30	2.0	3.1	6.75
40	1.45	2.2	5.0
50	1.2	1.9	4.0
60	1.0	1.6	3.25

5.3.3 Problem Areas

Analyses of the free-field overpressures generated by the HIRT facility show that the most likely affected structures, in terms of damage, are the AEDC buildings which are located approximately 3000 ft from the facility. These buildings are the model shop, the instrument calibration laboratory and the fire, police and communications building.

Of the above three buildings, the model shop is the most critical because of its sheet metal walls and large glass window area. A photograph of the model shop is shown in Figure 52 looking approximately due south. The largest window area shown in Figure 52 is approximately 42 ft long by 28 ft high, and is partitioned by five vertical and three horizontal stiffeners. Thus each major window panel area (i.e., bounded by heavy stiffeners) is approximately 49 square feet. In addition, each major window panel area is sub-divided into five panes vertically and four panes horizontally. Thus the dimensions of an individual glass pane are approximately 12 in. by 17 in. In determining the critical free-field overpressures which would cause glass breakage in the model shop, the stiffening effect provided by the spacers between the small glass panes has been ignored since it will effectively be quite small. Thus the basic glass panels which have been investigated are those formed by the heavy stiffeners, that is, the effective glass window area has been assumed to be 49 square feet. Moreover, the window glass has been assumed to be single-strength rather than double-strength glass.

Utilizing the glass breakage criteria defined in Section 5.3.2 it can be concluded that for single-strength glass having an area of 49 square feet, the maximum safe free-field overpressure would be approximately 1.2 lb/ft^2. This figure is based upon extrapolation of the single-strength glass curve to accommodate large panel areas. Since the anticipated free-field overpressure from the HIRT facility at 3000 ft is approximately 1.05 lb/ft^2 (see Figure 50) it may be concluded that there is a very high probability that glass breakage will result.

The walls of the model shop are constructed from ribbed industrial siding (approximately 0.04 in. thick) faced on the inside of the building by 0.04 in. thick metal sheeting. The dimensions of an individual wall panel between vertical and horizontal stiffeners are estimated to be on the order of 8 ft vertically by about 20 ft horizontally, and the surface weight is approximately 0.7 lb/ft^2. Calculations indicate that the fundamental resonance of the model shop wall panels is approximately 20 Hz. Since these walls have been designed to withstand significant wind loads, and can be considered to be primary structure, no damage from the starting shock is anticipated. The minimum design load for this type of corrugated industrial siding is about 20 lb/ft^2. Thus it is expected that free-field overpressures could reach 5 lb/ft^2 before any damage would occur.

For the broad-band noise environment, calculations indicate that a one-third octave band sound pressure level of approximately 130 dB (centered at the fundamental resonance of 20 Hz) would be required to produce maximum stress of 1000 $lb/in.^2$ in the metal skin. Thus the effects of the broad-band noise on the model shop are expected to be negligible in terms of damage.

The nearest residential structures are estimated to be approximately 8000 ft from the HIRT facility. At this distance the starting shock overpressures and the broad-band noise levels will have diminished to such an extent that no structural damage is anticipated. The free-field overpressure will be approximately 0.4 lb/ft^2 and the overall sound pressure level will be about 107 dB.

5.3.4 Summary of Expected Damage

A summary of the expected effects upon building-type structures is presented in the table on the following page for the starting shock environment. As mentioned earlier, the broad-band noise environment is not as critical as the starting shock environment for either AEDC buildings or surrounding residential buildings.

TABLE XVIII

ASSESSMENT OF STRUCTURAL DAMAGE DUE TO HIRT STARTING SHOCK

Structure Type	Approx. Distance from HIRT Facility (ft)	Most Critical Structural Elements	Critical Free-Field Overpressure to Cause Damage (psf)	Free-Field Overpressure Due to HIRT Starting Shock	Remarks
Model Shop	3,000	Single-Strength Window Glass - Effective Pane Area ≑ 49 ft^2	1.2 psf	1.05 psf	Possible Glass Breakage
		Metal Panelling	5.0 psf	1.05 psf	Possible Rattling-No Anticipated Damage
Instrument Calibration Laboratory	3,000	None (Brick Construction- No windows)	---	---	No Anticipated Damage
Fire Station	3,000	Window Glass- Effective Pane Area ≑ 20 ft^2	2.9 psf	1.05 psf	Possible Rattling-No Anticipated Glass Breakage
Residential Structure	8,000	Single-Strength Window Glass- Maximum Pane Area ≑ 20 ft^2	2.9 psf	0.405 psf	No Anticipated Damage

From the above table, it can be seen that glass breakage in the model shop walls is highly possible as a result of the starting shock. Otherwise no structural damage is anticipated for the remaining AEDC buildings nor for surrounding residential structures. However, care must be exercised when storing large flexible items, such as metal sheeting, in and around the model shop area, since the strength of the starting shock is sufficient to dislodge any unrestrained items.

6.0 SPECIAL CONSIDERATION FOR NOISE PROTECTION AND CONTROL

The assessment of HIRT noise impact on the environment indicates that noise is of marginable acceptability for several areas within the AEDC and surrounding residential communities. In many instances, the probability of a "potential" problem area becoming an "actual" problem area cannot be readily evaluated until experience with the full-scale facility is gained. Nonetheless, it is important that methods of noise control be explored at this stage of facility development in order to arrive at methods of limiting noise impact to acceptable levels before the fact. Fortunately, a number of alternative methods of noise protection and control are available to AEDC without seriously affecting the capabilities of the facility, its usage, or impacting its economic status.

However, before discussing the various methods of noise protection and control, it should be noted that extensive tests will be performed during the facility shake-down period which will facilitate the acquisition of acoustic data for the purpose of defining the actual noise characteristics of the full-scale facility. With any new system of the size and complexity of the HIRT facility, it is necessary to perform extensive shake-down tests over a limited range of its operational capability in order to check the system and to familiarize personnel with the operation of facility components. These tests will provide acoustic data at reduced power levels which can be used to specify actual noise levels in areas surrounding HIRT.

Although considerable confidence can be placed in the predicted noise environments which have been made to this point, the final assessment will be made based on actual noise of the full-scale facility. Acoustic measurements at low power runs will clearly reveal any problem areas which must be resolved before proceeding to high-power run conditions.

The following is a listing of available methods of noise protection and control. The first two methods are for noise protection and they will be implemented, at least to some degree, prior to and during initial operation of the facility. The third and fourth methods are for noise control and they will be implemented on an "as required" basis.

- Protection by Control Areas
- Protection by Warning/Monitoring Systems
- Control by Facility Operating Schedule and Usage
- Control by Facility Soundproofing Modifications

It should be noted that the first two methods do not affect the noise generated by HIRT but rather depend on protecting the receiver from excessive noise levels. The third and fourth methods of control depend on altering the level of noise generated at the source. These methods of protection and control are discussed separately in the following subsections.

6.1 Protection by Control Zones

The noise produced by HIRT for areas in close proximity to the facility will be too excessive to permit access by personnel without control. Personnel entering and leaving areas of potentially excessive noise must be protected from accidental exposure during HIRT runs. One method of controlling the exposure of personnel to HIRT noise is through the designation and control of areas subjected to excessive noise levels. These areas will be designated as Control Zones. In general, a control zone is defined herein as an area within which HIRT noise may be potentially hazardous or may produce excessive annoyance to someone within the area during a HIRT run. Several classes of control zones will be defined, depending on the degree of control required. The following are tentative control zones and the requirements for their level of control.

Control Zone 1 — Restricted Area

Control Zone 1 will be a "restricted area" distinguished by the following level of control:

1. Fenced area at approximately 3000 foot radius from the HIRT exhaust stack.

2. Personnel will have access to this area but will not be permitted outdoors during the warning period corresponding to a HIRT run. Controlled, limited, access will be available only on a "need—to-be-in-the-area" basis during normal working hours corresponding to when testing may be scheduled.

3. Hearing protection will be provided to all personnel entering this zone as a safety measure.

4. A Class A warning system (see discussion on warning systems) will be provided for this zone.

5. A safety interlock system will be provided which will be easily accessible to outdoor personnel.

Control Zone 1 is the most hazardous noise zone and corresponds to an area within which noise levels may be expected to produce hearing damage in the event outdoor personnel are exposed without hearing protection. Except for noise-induced hearing loss, there does not appear to be any extra-aural noise disease which may be produced by HIRT noise. However, within 500 feet of HIRT, the noise produced for near-maximum mass flow conditions may cause nausea, vomiting, headaches and other vegetative reactions which should be avoided. In general, most of the outdoor activity for HIRT will be within 1000 feet of the exhaust stack with other area within approximately 3000 feet radius being areas of little activity with the exception of facility traffic. Because of

the risks involved in permitting access to within 1000 feet of HIRT during test periods and because traffic to the facility should be restricted during tests, outdoor activity will be prevented within Control Zone 1 during test periods. Also, the boundary of Control Zone 1 corresponds, roughly, to the maximum acceptable noise level for industrial noise exposure. The boundary of Control Zone 1 could be moved to within 1000 feet of the exhaust stack; however, the need to protect other people who may be in the area such as hunters, would require a second fence. Therefore, it appears practical to limit Control Zone 1 to the 3000 foot radius with possible minor exceptions. For normal test programs, the perceived noise levels outside of Control Zone 1 will not exceed 120 PNdB; however, for near-maximum mass flow conditions, the perceived noise level may approach 130 PNdB at the boundary. For a single exposure, this level is within acceptable limits for unprotected personnel. Because of the low percentage of runs which will be conducted at maximum mass flow rate, the probability of an unprotected person being near the boundary of Control Zone 1 is extremely low and any exposure may be considered as a single event. It should be noted that Control Zone 2, discussed below, is immediately adjacent to Control Zone 1, and AEDC personnel working outdoors in this area will be required to wear hearing protection during HIRT runs.

Control Zone 2 — Protected Area

Control Zone 2 will be a "protected area" distinguished by the following level of control:

1. A rectangular area within a 4000 foot radius from HIRT between 1st Street and Control Zone 1 for the protection of personnel working at the following facilities:

    a. Model Shop

    b. Chemical and Metalurgical Building

    c. Instrumentation Calibration Laboratory

    d. Fire, Police and Communication Building

2. Personnel will be permitted to work outdoors in this zone, but will be required to wear hearing protection during HIRT runs.

3. A Class A warning system will be provided for this zone.

Of primary concern in Control Zone 2 are personnel working outdoors behind the buildings listed in (1) above. Reflections of HIRT noise from the exposed sides of these buildings may cause a 3 to 6 dB increase in noise level for these personnel. Since their work tasks may require daily exposure to HIRT noise, these personnel will be required to wear hearing protection during HIRT runs.

Control Zone 3 — Warning Area

Control Zone 3 will be a "warning area" distinguished by the following level of control:

1. A rectangular area within 6000 foot radius of HIRT between 1st Street and 4th Street.

2. Personnel will be permitted to work outdoors in this zone without hearing protection.

3. A Class B warning system will be provided for this zone.

Noise levels within Control Zone 3 will not produce hearing damage, although levels may be sufficiently large to cause considerable annoyance if workers are not warned prior to HIRT runs. Thus, a visual warning system will be employed to notify personnel within this zone of HIRT run status.

The control zones described above are designed to minimize the physiological and psychological impact of HIRT noise as presently envisioned. During facility shake-down tests, actual noise levels will provide a more meaningful basis for the judicious specification of control zones. For this reason, the control zones described above are tentative in both the area of coverage and the level of control since both are subject to the measurement of actual noise environments during facility shake-down tests.

6.2 Protection by Warning/Monitoring Systems

A warning system will be required to notify outdoor personnel of HIRT run status for areas of potentially hazardous or excessively annoying noise levels. At least two basic types of warning systems are presently envisioned as being required.

1. Class A Warning System: The Class A warning system will consist of both visual and aural warning components which are controlled directly from the HIRT facility control room. Visual warning components will consist of warning lights located at strategic points within the control zone which indicate the status of a HIRT run. Color coded beacons will be employed as follows:

   - Green Beacon - Area clear for unprotected access — all control zones

   - Yellow Beacon - Control Zone 1 - Evacuate the Area
     - Control Zone 2 - Hearing Protection Required
     - Control Zone 3 - For Warning Purposes Only

- Red Beacon - Control Zone 1 - Area Must be Clear of All Personnel
  - Control Zone 2 - Area Must be Clear of Unprotected Personnel
  - Control Zone 3 - For Warning Purposes Only

The time of activating the various color beacons prior to a HIRT run is subject to further study; however, a tentative schedule is as follows:

Green Beacon:	HIRT run will not occur for at least 15 minutes. For periods of heavy testing when runs will occur within 30 minute intervals, the green beacon will not be activated.
Yellow Beacon:	HIRT run may occur within 15 minutes. For periods of heavy testing, when runs will occur within 30 minute intervals, the yellow beacon will remain activated for periods in excess of 15 minutes before a run.
Red Beacon:	HIRT run will occur within 5 minutes.

All beacon warning systems will bear a title denoting "HIRT Noise Warning System" with appropriate description of warning lights for the control zone.

The aural warning system will be a public address system which can be clearly understood within Control Zones 1 and 2. HIRT facility control personnel will provide appropriate aural warning to coincide with the activation of the various phases of visual warning. Also, a countdown to run will be performed at appropriate intervals within 5 minutes of a run.

2. Class B Warning System: The Class B warning system will consist of only visual warning components as described in (1) above.

A monitoring system will be employed at strategic points at AEDC and surrounding areas for determination of noise levels. Variations in noise level may be expected due to atmospheric variations. During high-wind conditions, close attention will be given to noise measurements by the monitoring system, particularly for severe test conditions, to preclude excessive noise levels for critical areas.

6.3 Control by Facility Operating Schedule and Usage

Noise annoyance factors for HIRT depend largely on the accumulative exposure to many runs of various levels of noise within a given time period. One method of controlling the noise annoyance is to maintain a low "Frequency and Intensity Factor", FIF, through judicious scheduling of runs. For normal test programs, the median value of FIF is 4, with larger values producing more annoyance and lower values producing less annoyance. A statistical analysis of projected HIRT usage shows that 80 percent of HIRT runs will have FIF between -3 and +8. In scheduling daily runs, FIF should be maintained as low as possible through appropriate mixing of run schedule, with the larger FIF schedules occurring during daylight hours. A schedule during daylight hours only has FIF for surrounding communities approximately 10 lower than an equivalent schedule at night. Weekend scheduling of high FIF tests would reduce the impact on AEDC personnel. The important point to note here is that noise control can be exercised through facility schedule and usage.

6.4 Control Through Facility Soundproofing Modifications

Analyses of the noise produced by the HIRT facility to this point indicate that adequate noise control can be achieved without the application of soundproofing to the facility. However, if experience with the facility indicates that the methods of noise protection and control are not adequate or that these methods are too restrictive on facility usage, then the application of soundproofing modifications is an alternative which will be explored. This method of noise control should be recognized as being feasible and within the state of the art in the event that experience with the facility necessitates its application.

7.0 CONCLUSIONS

The environmental impact of HIRT noise on people, animals and structures has been investigated. Acceptable noise limits were determined from a comprehensive review of noise impact literature. Because of the quiet rural nature of the vicinity surrounding AEDC, community noise limits determined in the present study are significantly lower than those generally applied to communities near large urban airports.

Comparison of expected HIRT noise to the recommended limits leads to the following conclusions:

1. The noise exposure forecast for residential areas in the surrounding communities of Hillsboro, Manchester and Tullahoma is within acceptable limits and adverse reactions to HIRT are not anticipated. However, the following are several potential problem areas which must be carefully studied by means of noise surveys during low-intensity HIRT shakedown operations:

   - Isolated rural homes near the AEDC boundary may experience noise sufficiently high to be annoying. Close monitoring of noise at these locations will be required to assure acceptability.

   - Noise levels at the hospital in Manchester approach permissible limits for hospitals. Noise monitoring at this location during shakedown is especially important to assure that possible unfavorable atmospheric conditions do not cause unacceptable noise levels.

   - Motorists on Interstate Highway I-24, passing within two (2) miles of HIRT, may be startled by the sudden noise. Although available information on startle reaction indicates there will not be any adverse effect other than annoyance, a final determination of necessary precautions can be made only after a survey of traffic shakedown operations.

2. No area outside the AEDC reservation will be exposed to noise levels which represent a health hazard.

3. Outdoor noise levels on the AEDC facility complex within 3,000 feet of HIRT exceeds that allowable for outdoor-unprotected workers. For the protection of these personnel, a system of control zones must be implemented. These zones will range from a fenced restricted area up to 3,000 feet from HIRT, to various classes of protection and warning zones up to 6,000 feet.

4. Indoor noise levels on the AEDC complex will be acceptable for uses such as workshops, but generally exceed acceptable levels for office use. Favorable attitude of AEDC personnel may make these higher levels acceptable; however, care will have to be exercised in the scheduling of runs.

5. Soundproofing required to protect HIRT operating personnel from hearing loss is easily attainable with conventional mortar and brick construction; however, special consideration should be given to office buildings at the HIRT site to preclude excessive annoyance to office personnel.

6. Provided community noise limits are observed, there will be no adverse effects on domestic animals. Wildlife will not be seriously affected outside a small zone very close to the HIRT exhaust stack. The ecological balance of the AEDC facility will not be adversely affected by HIRT noise. As a precaution against damage due to possible startle reaction, large mammals should be evacuated from the 3,000 foot restricted zone.

7. No damage to AEDC buildings is anticipated. However, one large window in the model shop will be exposed to overpressures approaching that necessary to break single strength glass and therefore may require the utilization of double strength glass.*

8. Noise control by HIRT operating schedule and usage provides a means of reducing noise impact for critical problem areas. Provided test programs can be scheduled in such a way that this method of noise control can be realized, facility soundproofing devices will not be necessary.

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*Subsequent to the preparation of this report, it was determined that the subject window is already equipped with double strength glass.

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FIGURES

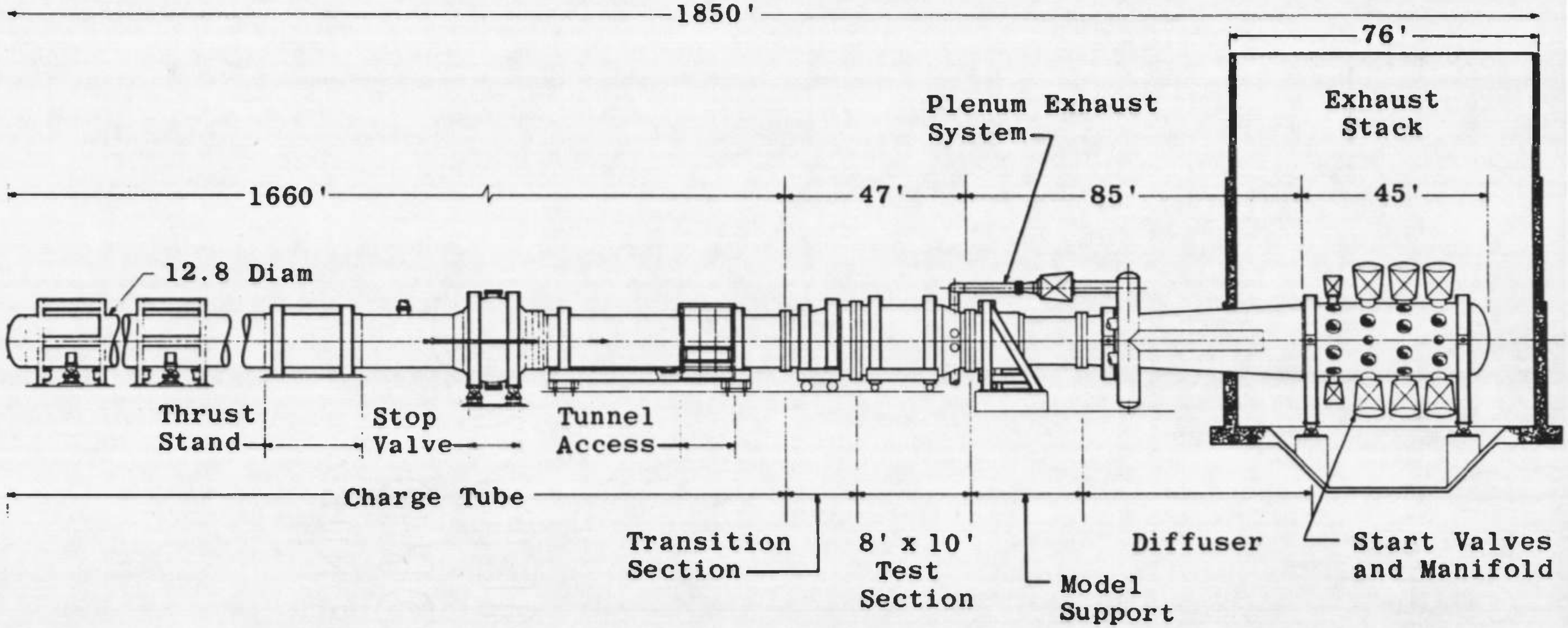


Figure 1. General Configuration of AEDC High Reynolds Number Tunnel (HIRT)

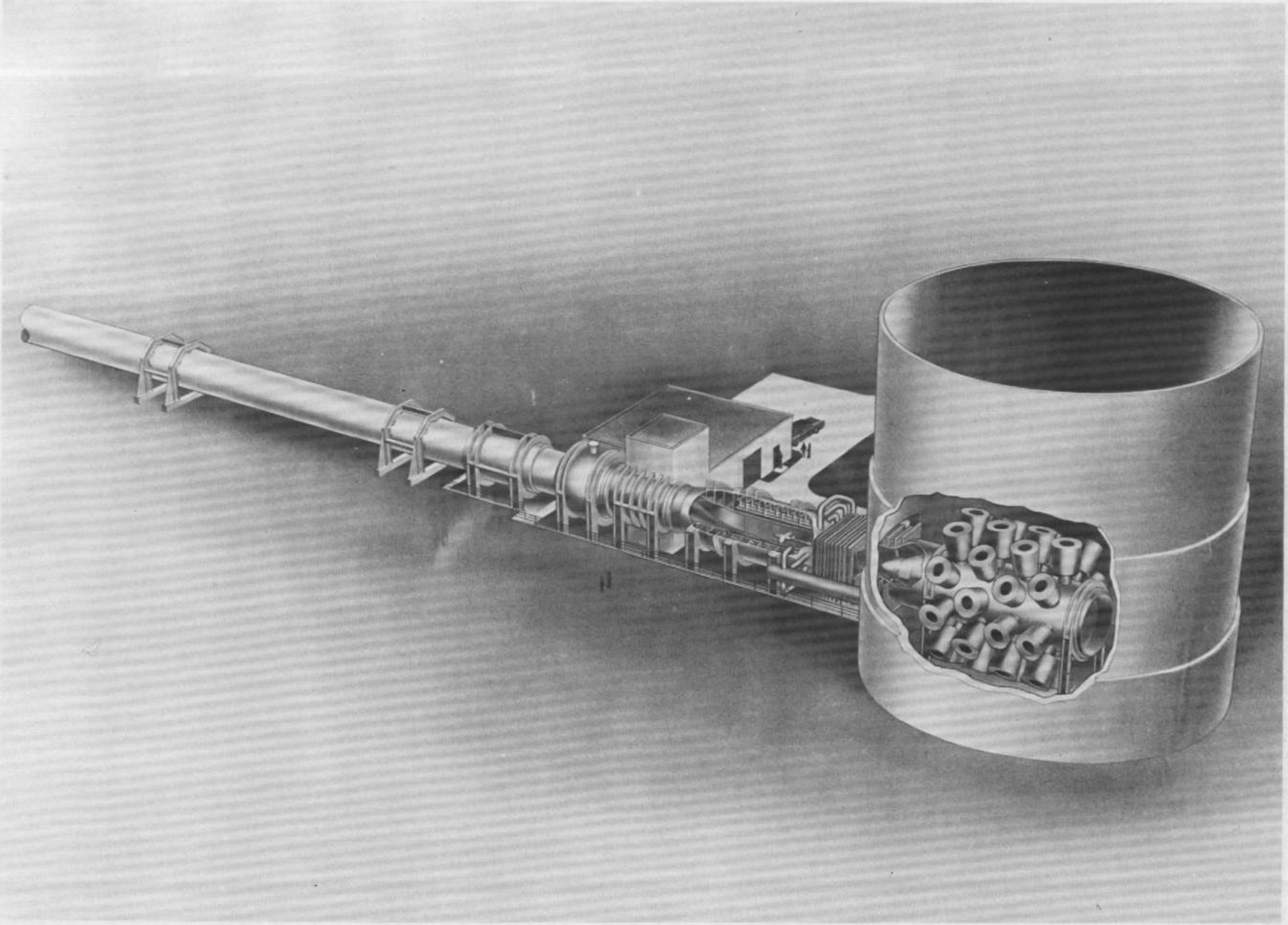


Figure 2. Artist's Conception of the AEDC - VKF High Reynolds Number Tunnel (HIRT)

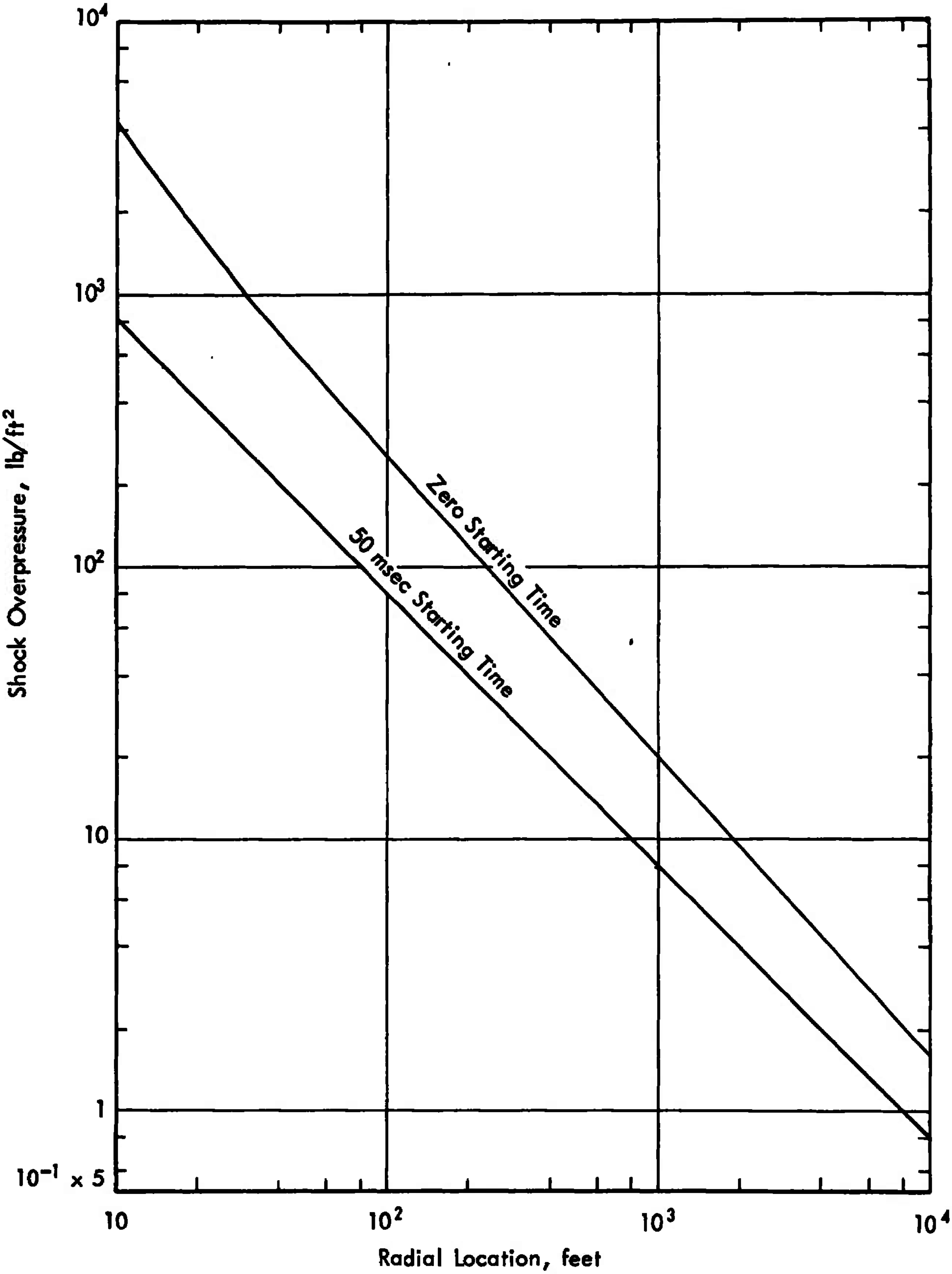


Figure 3. Variation of Starting Shock Overpressure with Radial Location, Mass Flux of 165,000 lb/sec

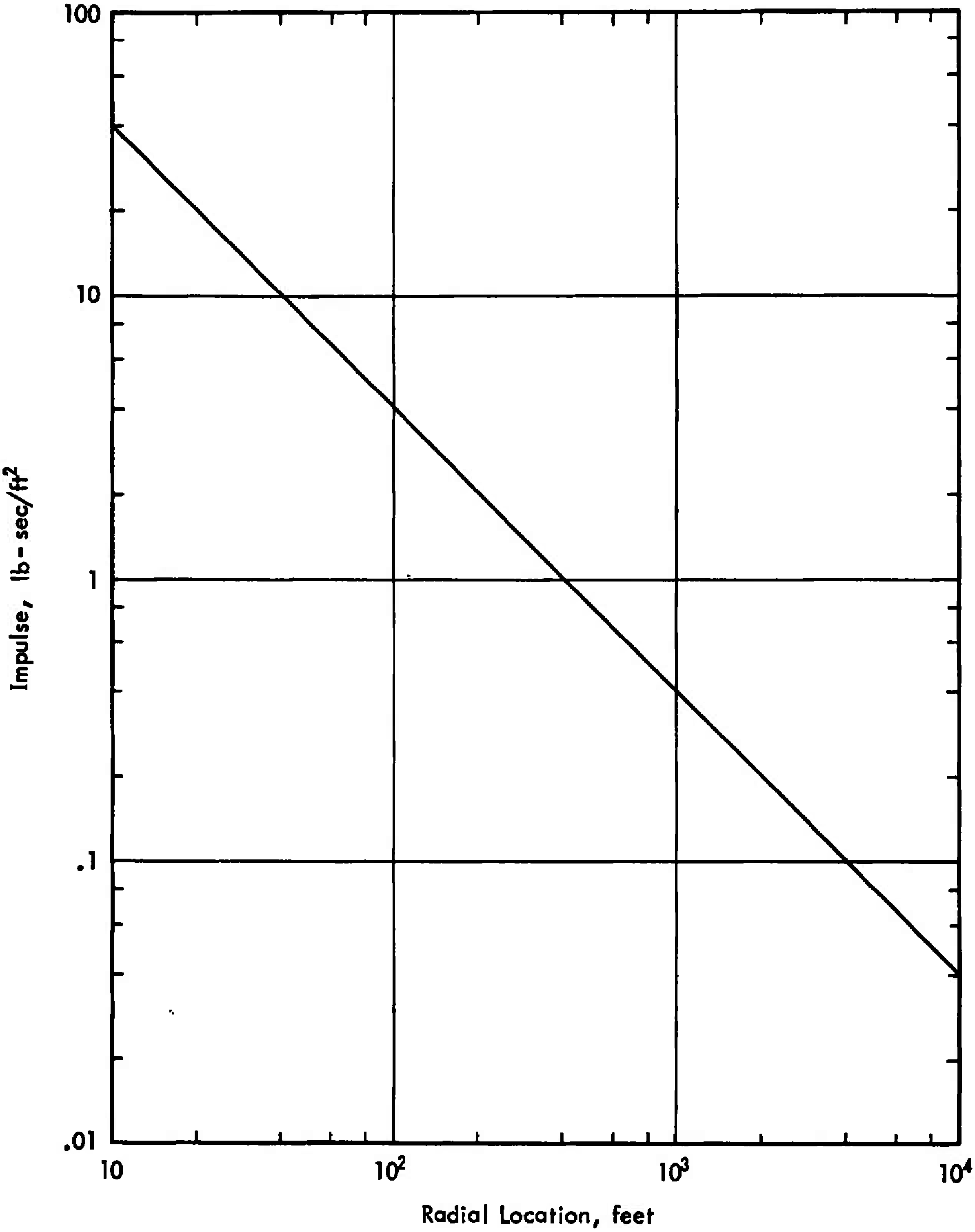


Figure 4. Variation of Starting Shock Impulse with Radial Location, Mass Flux of 165,000 lb/sec

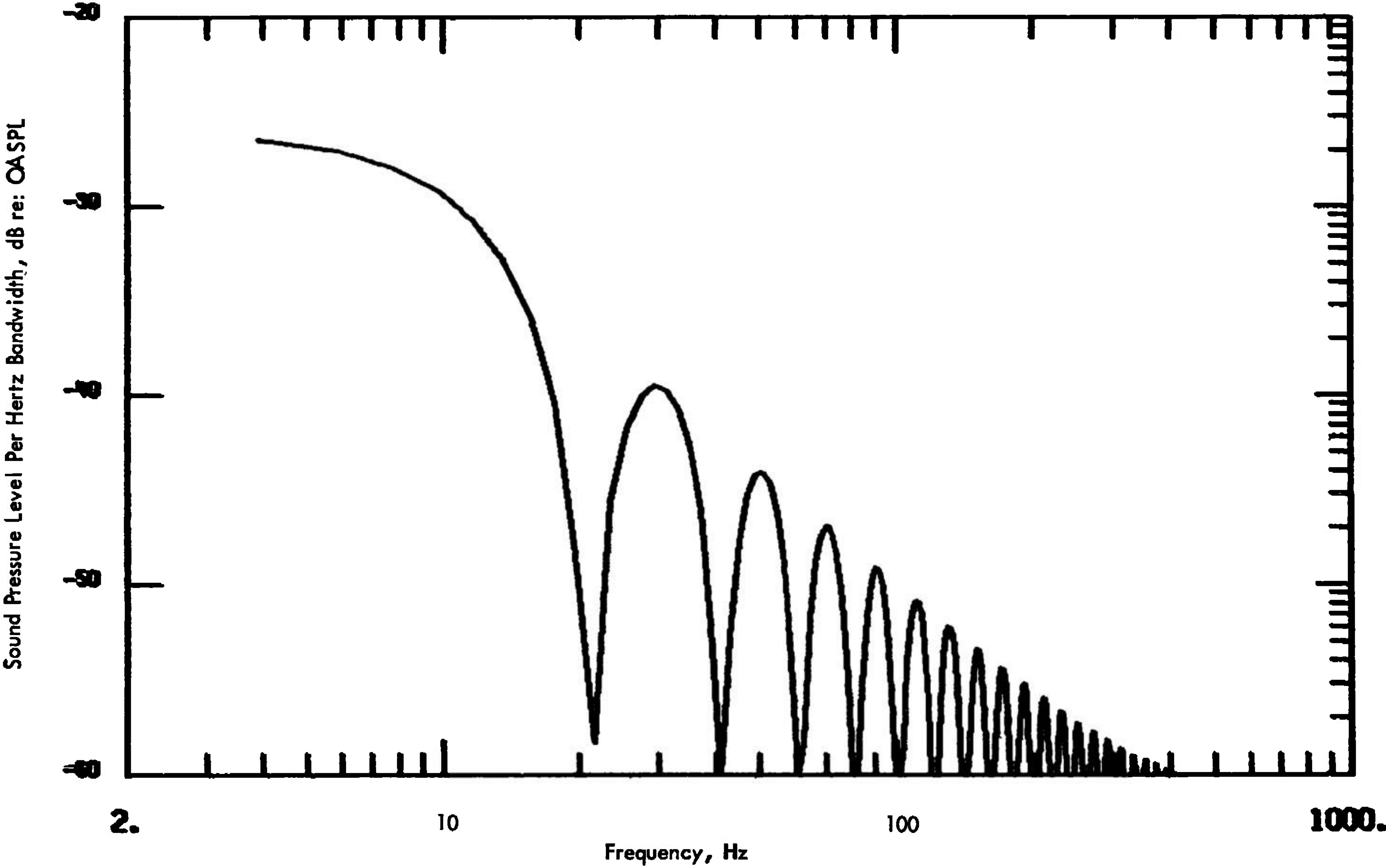


Figure 5. Sound Pressure Level Spectral Density for Starting Shock at the Valve Throat

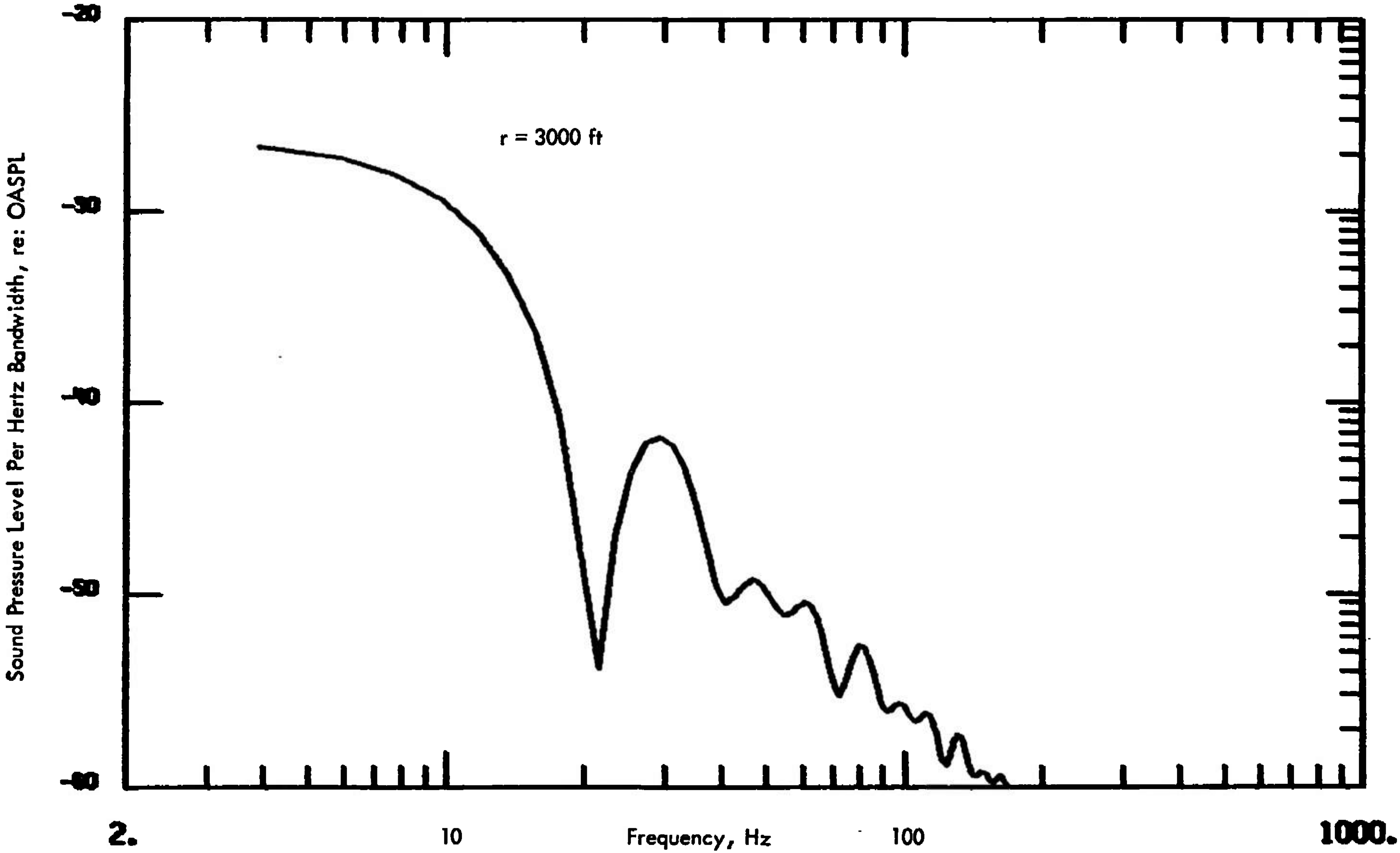


Figure 6. Sound Pressure Level Spectral Density for Starting Shock in the Far Field

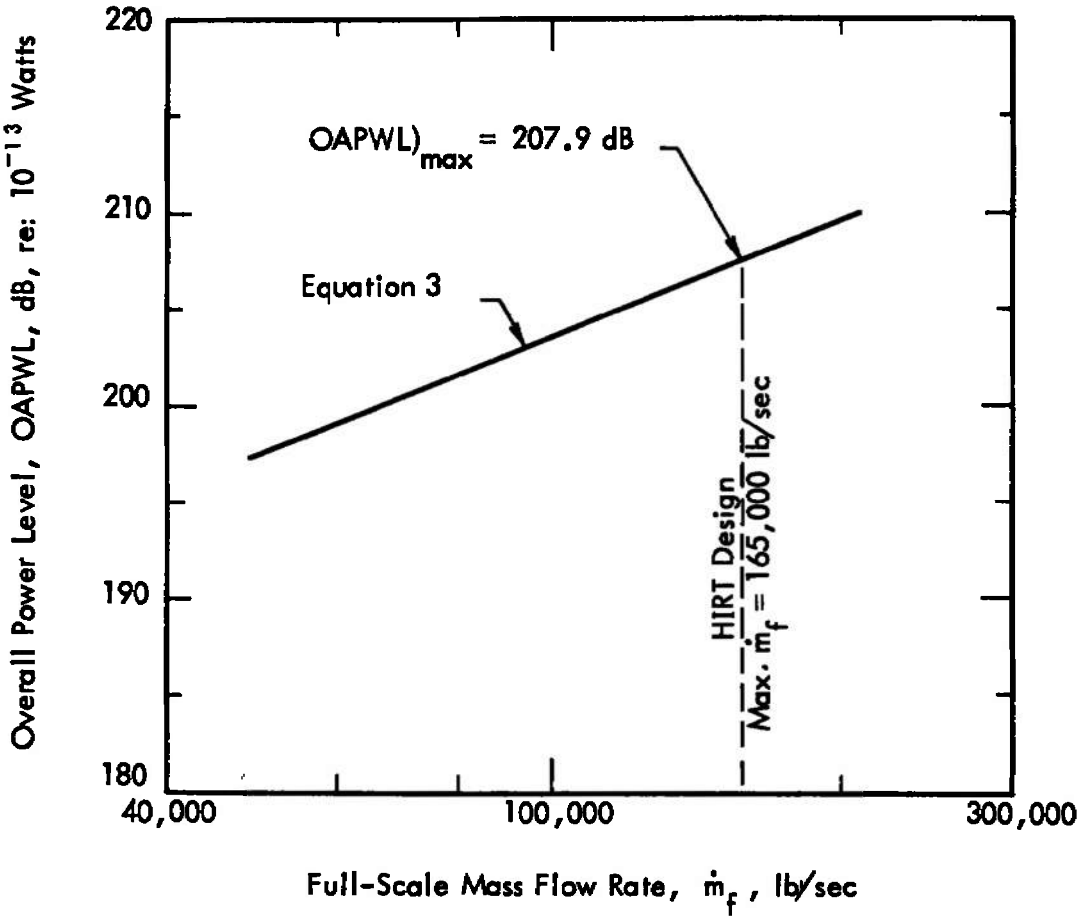


Figure 7. Variation of Predicted Overall Power Level with Mass Flow Rate for Full-Scale HIRT Facility

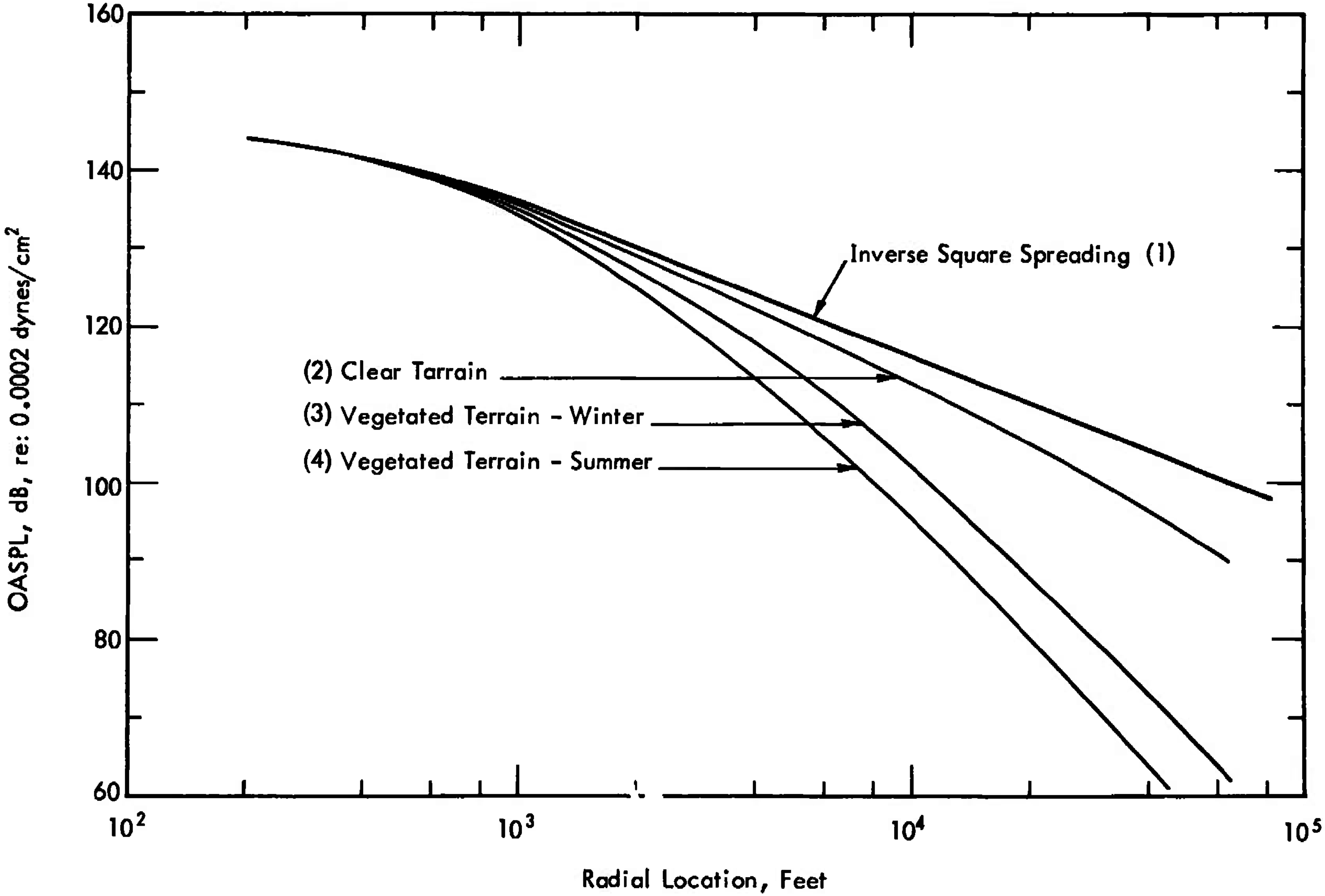


Figure 8. Variation of Overall Sound Pressure Level with Radial Location for Exhaust Flow Noise, Mass Flux of 165,000 lb/sec

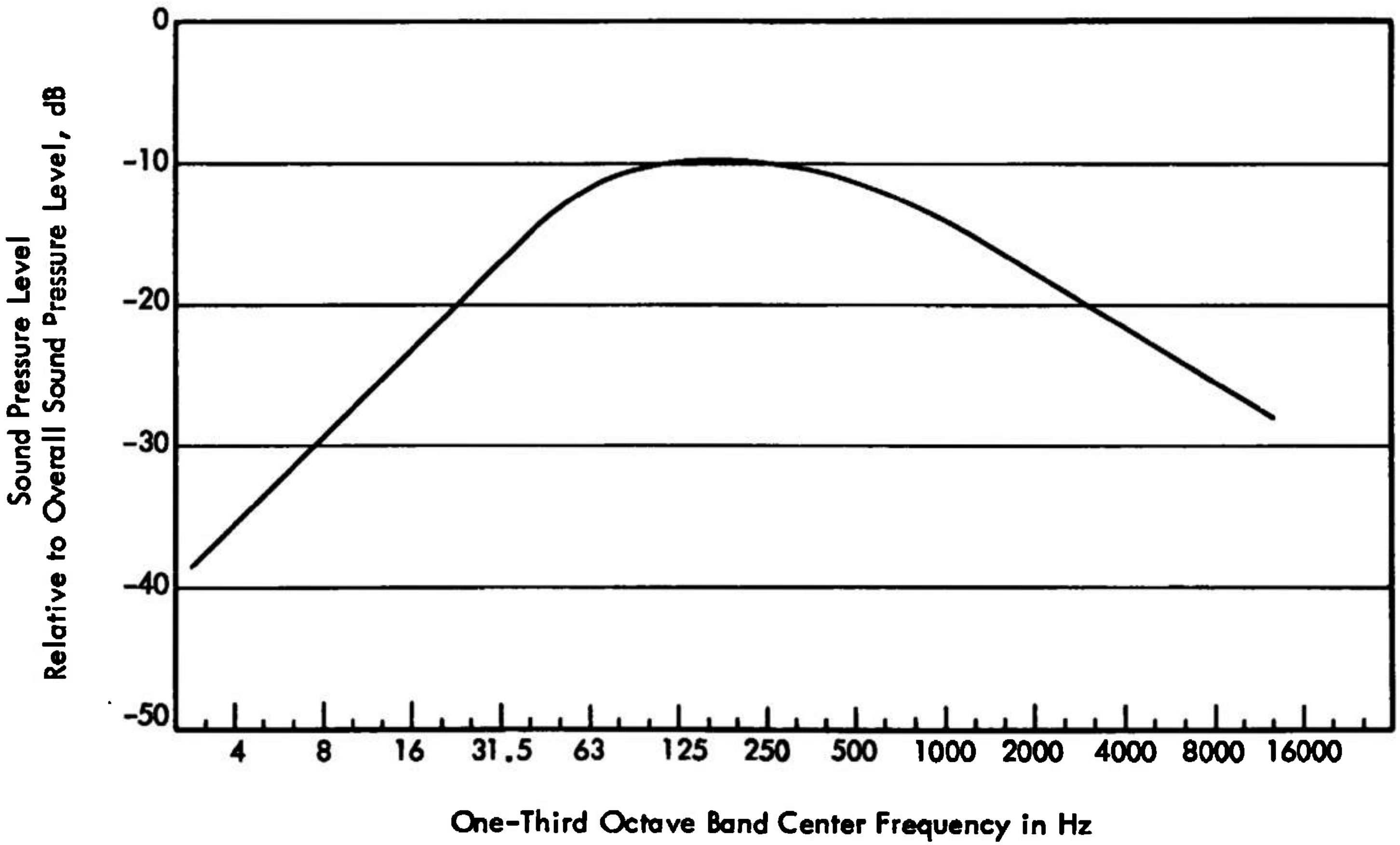


Figure 9. Predicted Full-Scale One-Third Octave Band Sound Pressure Level Relative to the Overall Sound Pressure Level as Derived from Experiment

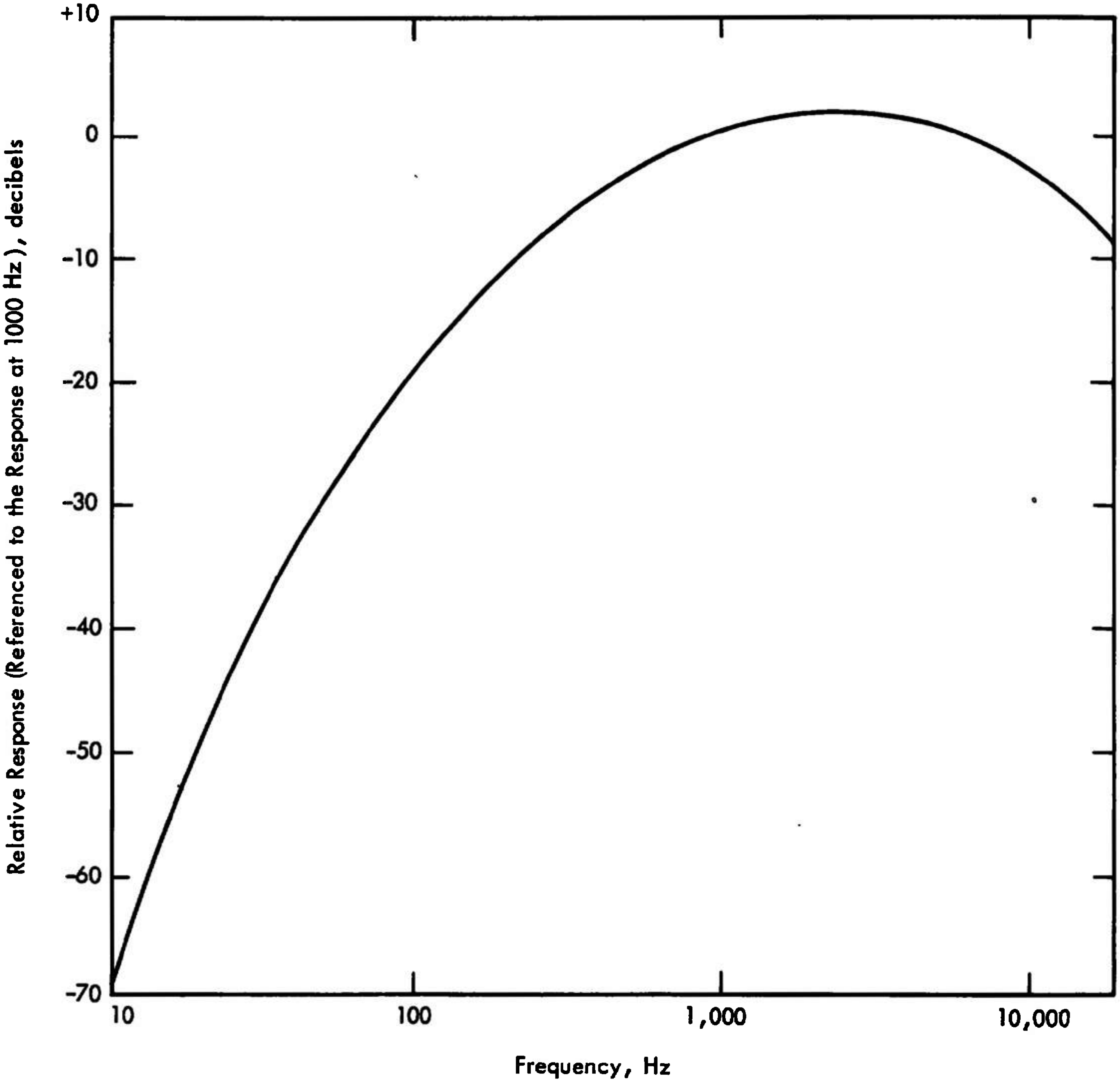


Figure 10. An Approximation to the Frequency Response of the Human Ear

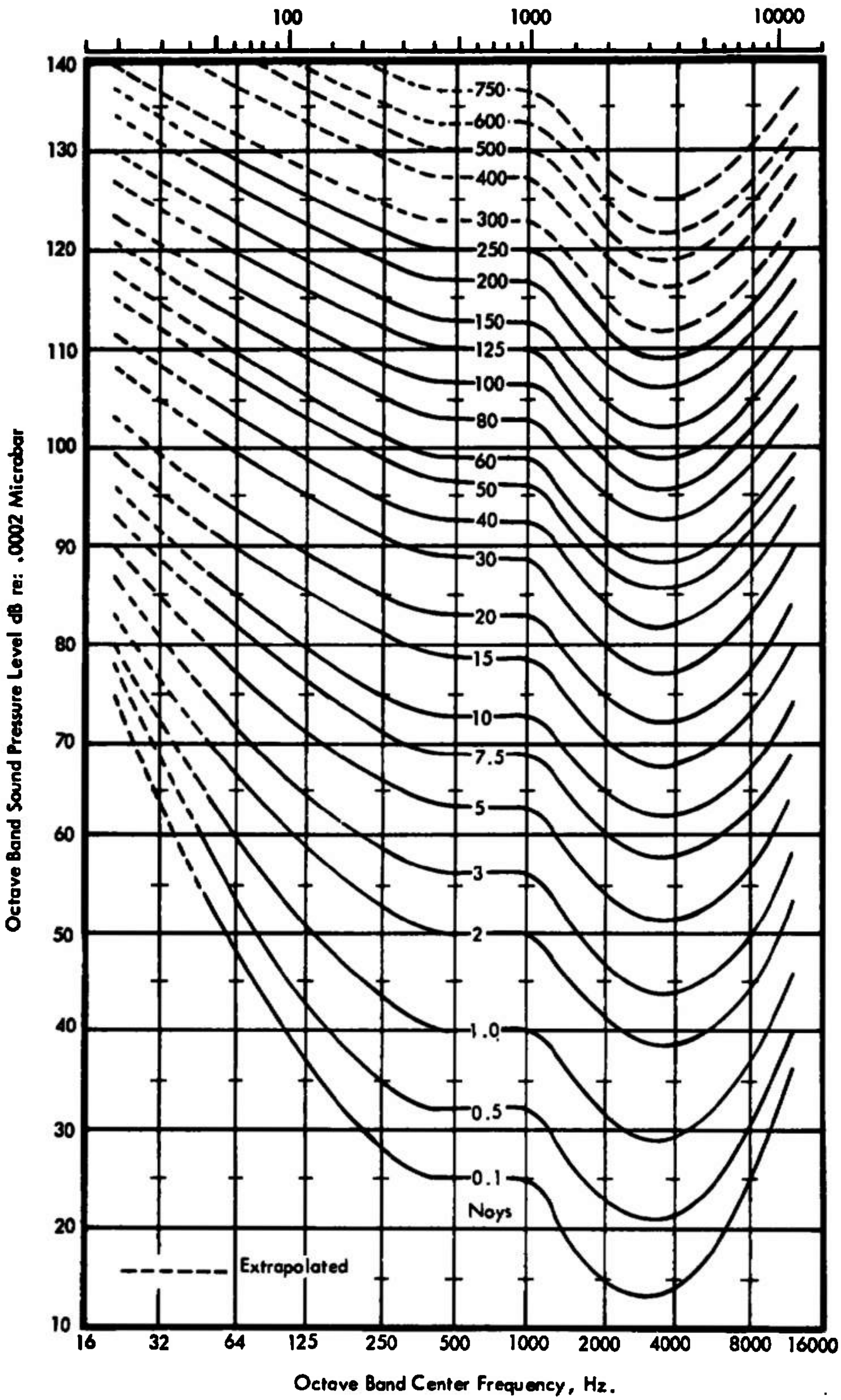


Figure 11. Equal Noisiness Contours for Bands of Noise After Kryter and Pearsons (Reference 8)

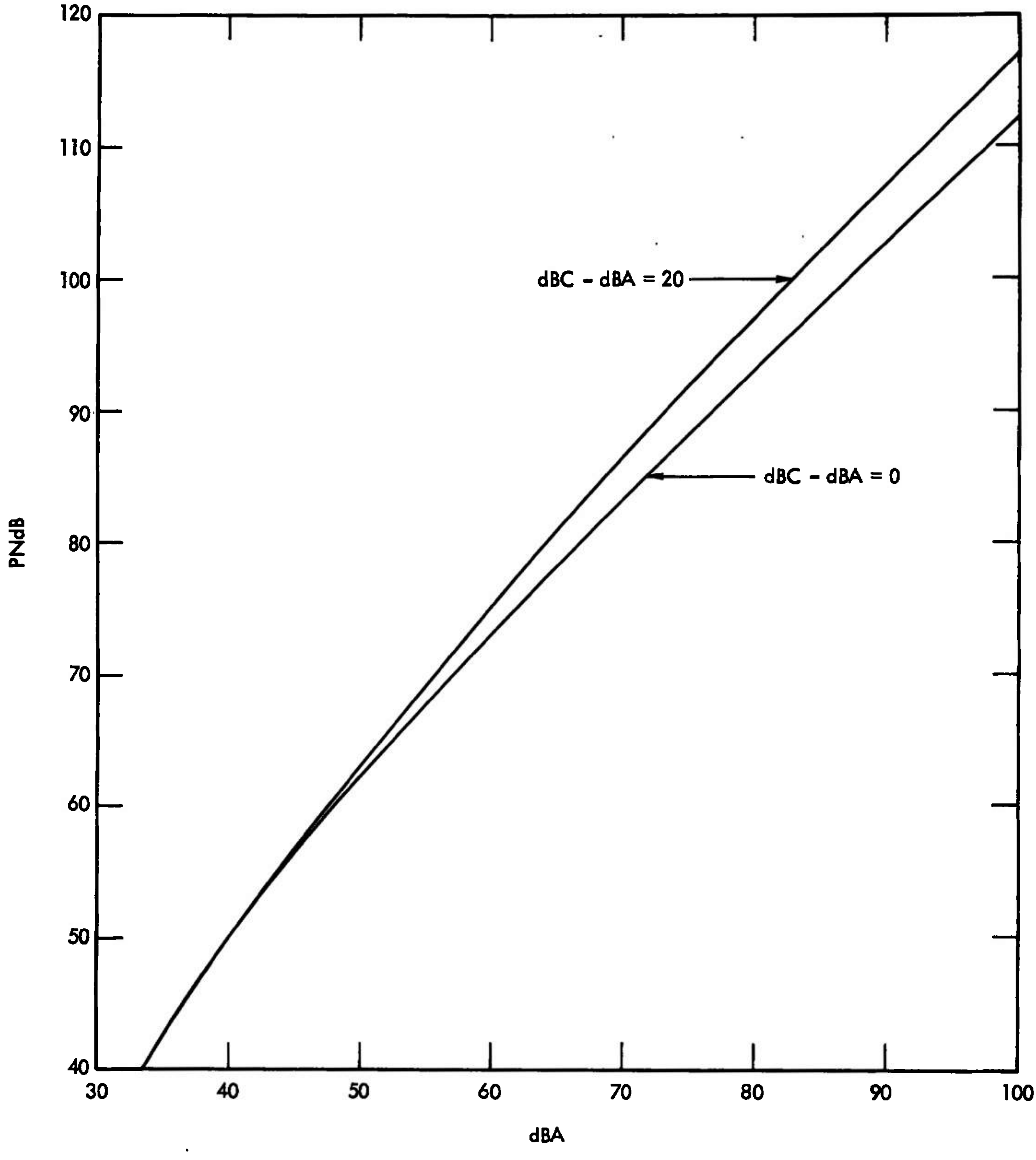


Figure 12. Correlation Between dBA and PNdB, after Botsford (Reference 10)

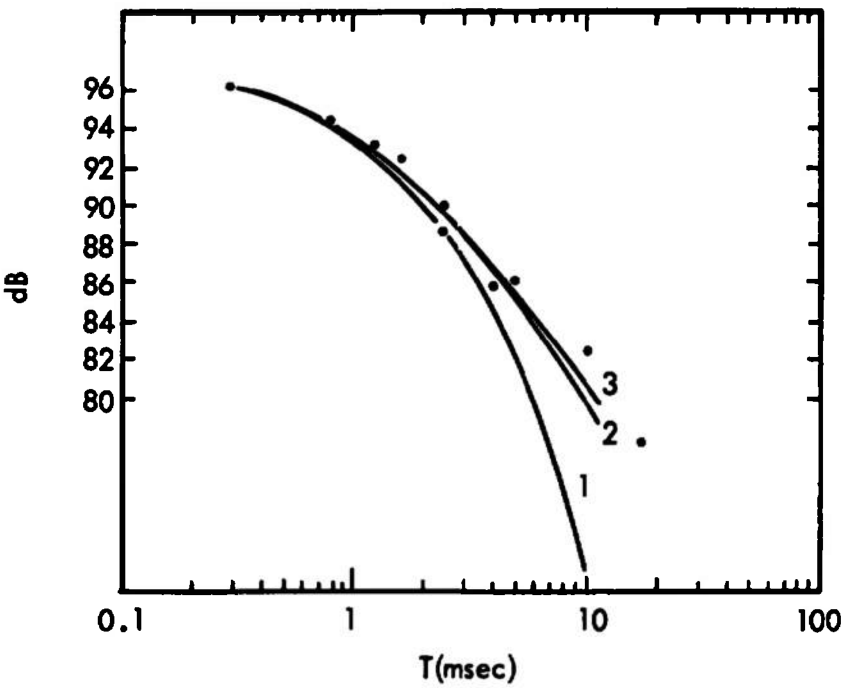


Figure 13. Shock Wave Loudness vs. Rise Time, from Zepler and Harel (Reference 11)

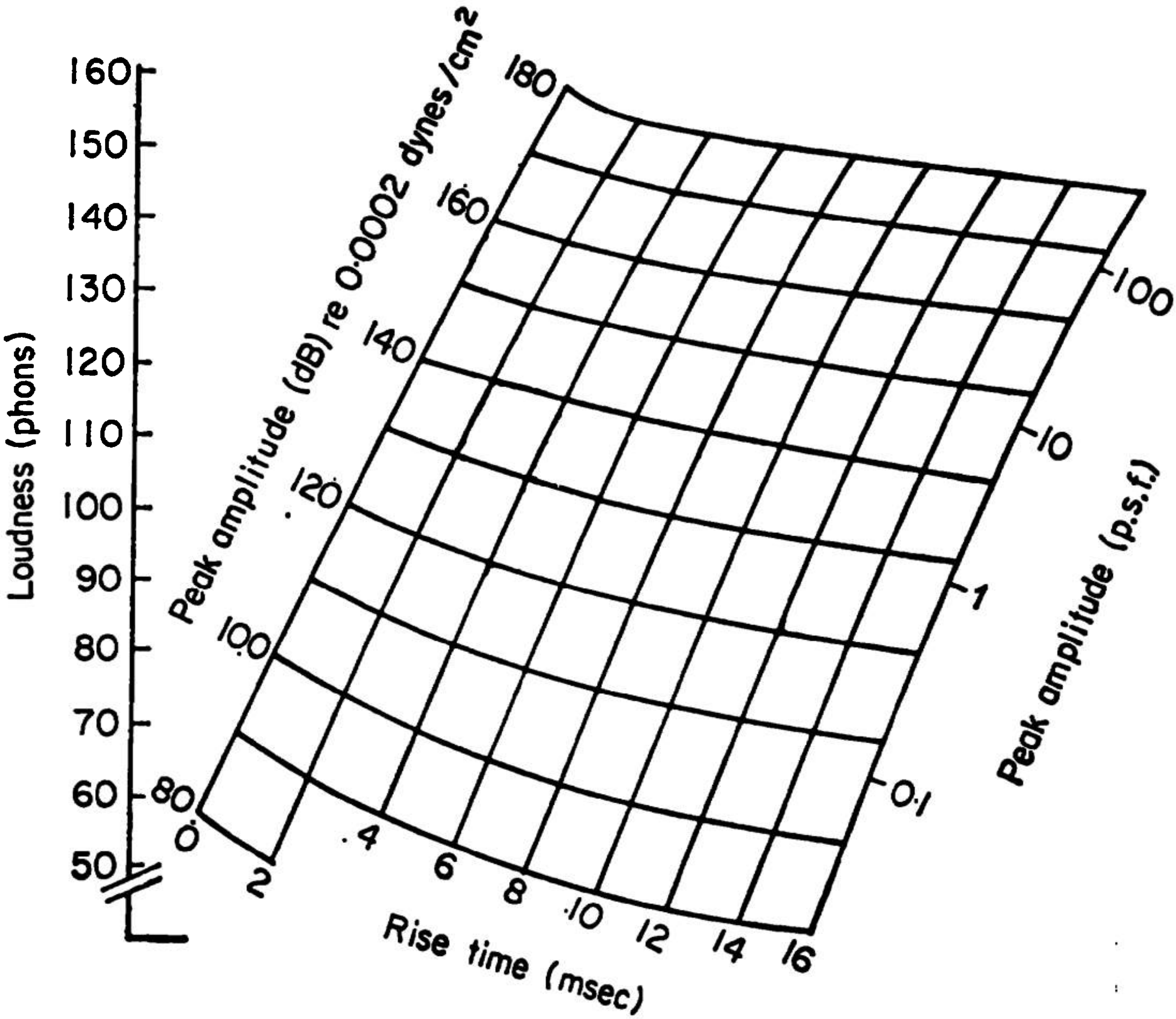


Figure 14. Loudness of N - Wave as a Function of Rise Time and Intensity After Pease (Reference 12)

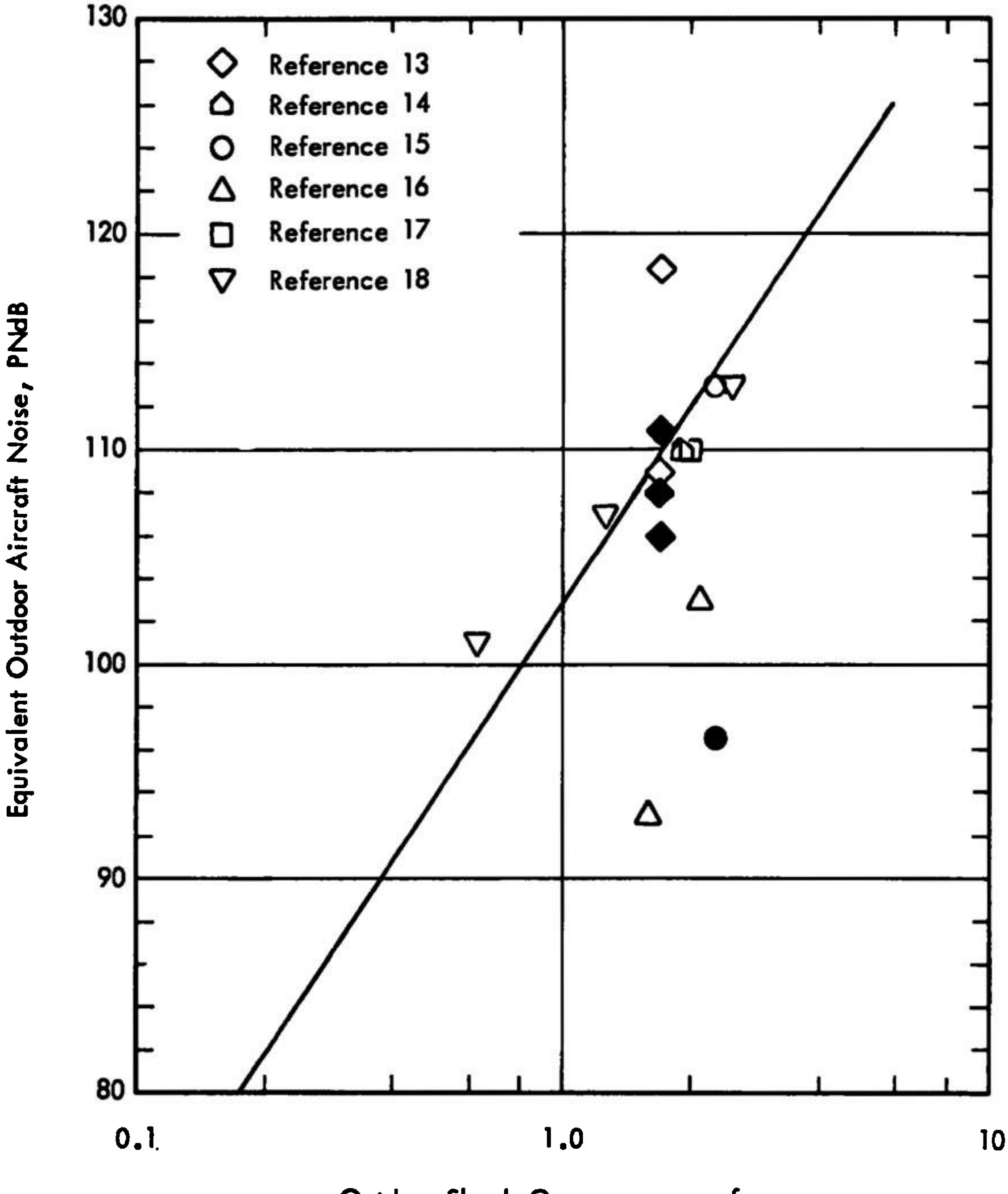


Figure 15. Equivalent Perceived Noise for Sonic Booms, Indoor Listening

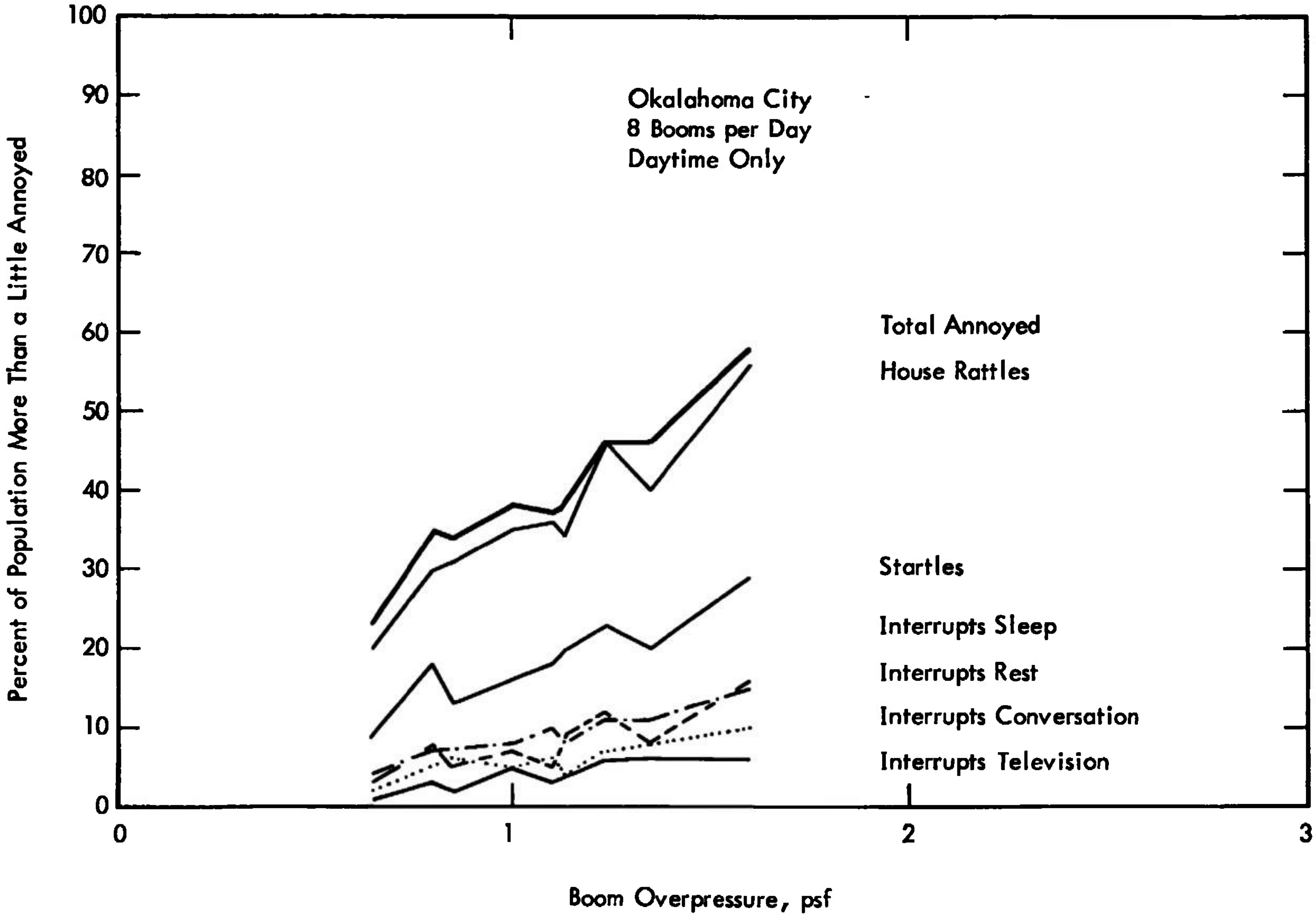


Figure 16. Community Annoyance from Sonic Booms (Reference 20)

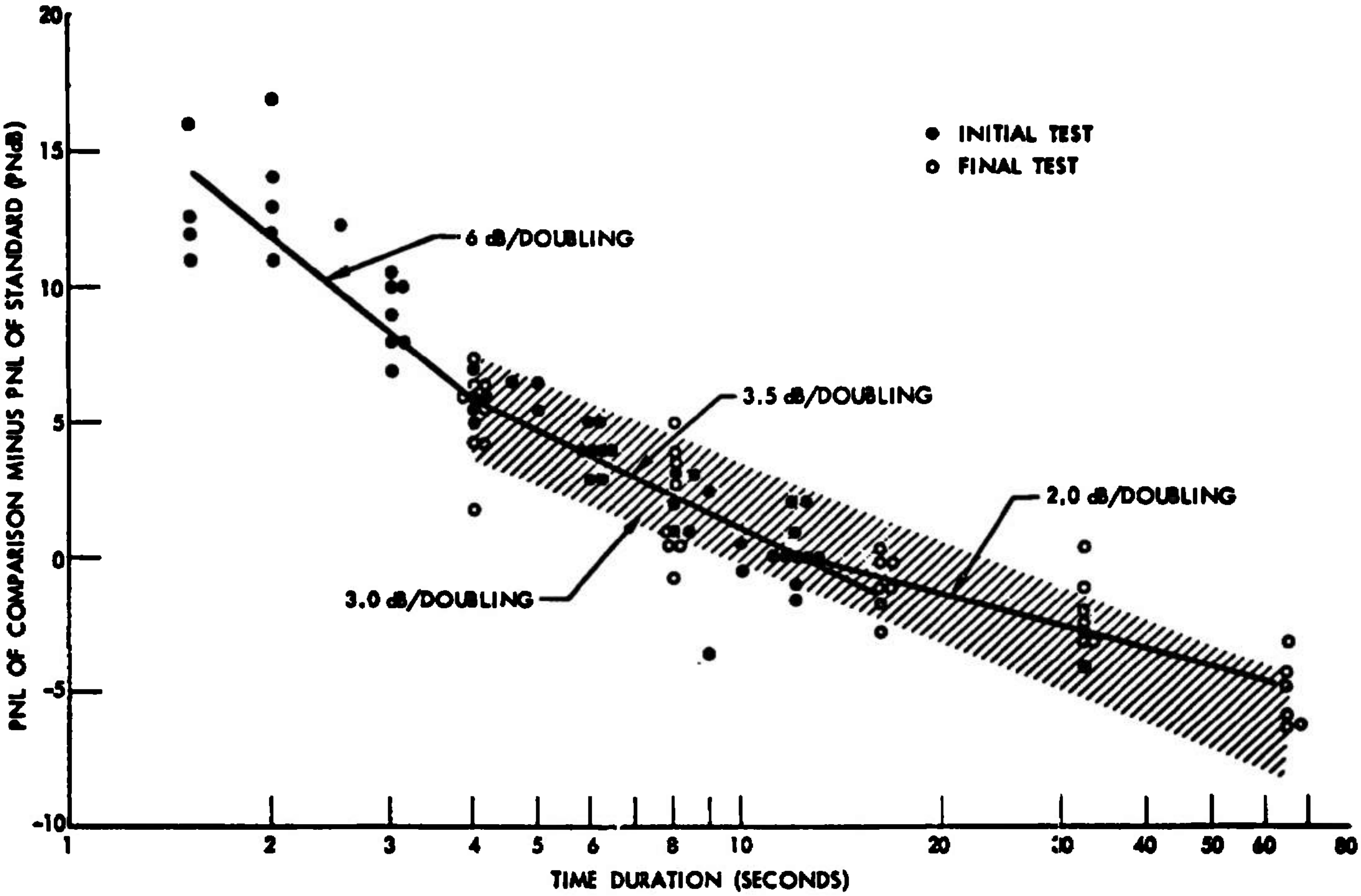


Figure 17. Summary of Equally Acceptable Noises of Various Durations (Combined Tests 1.5-64 sec)

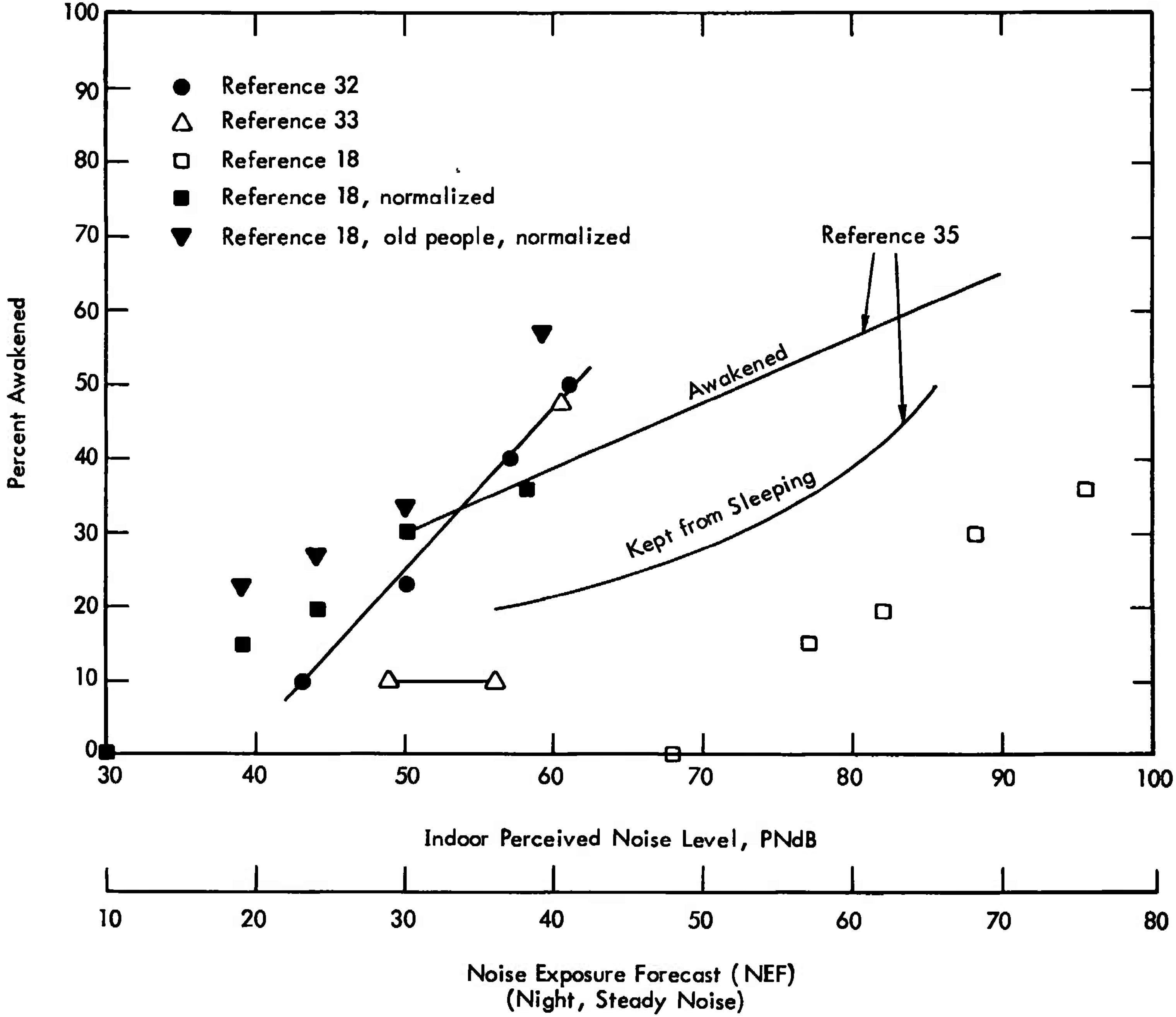


Figure 18. Disturbance of Sleep by Noise

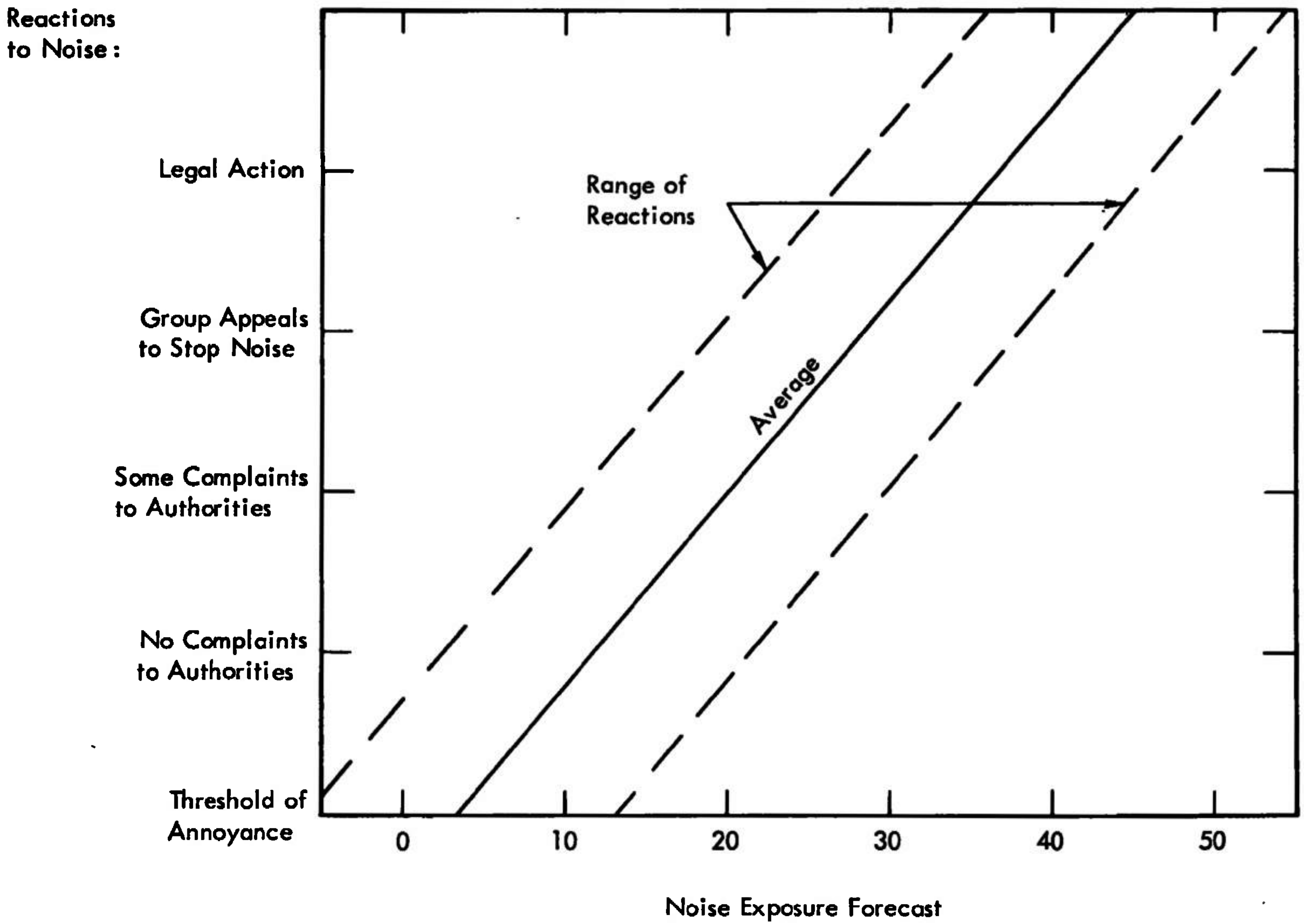


Figure 19. Community Response to Noise

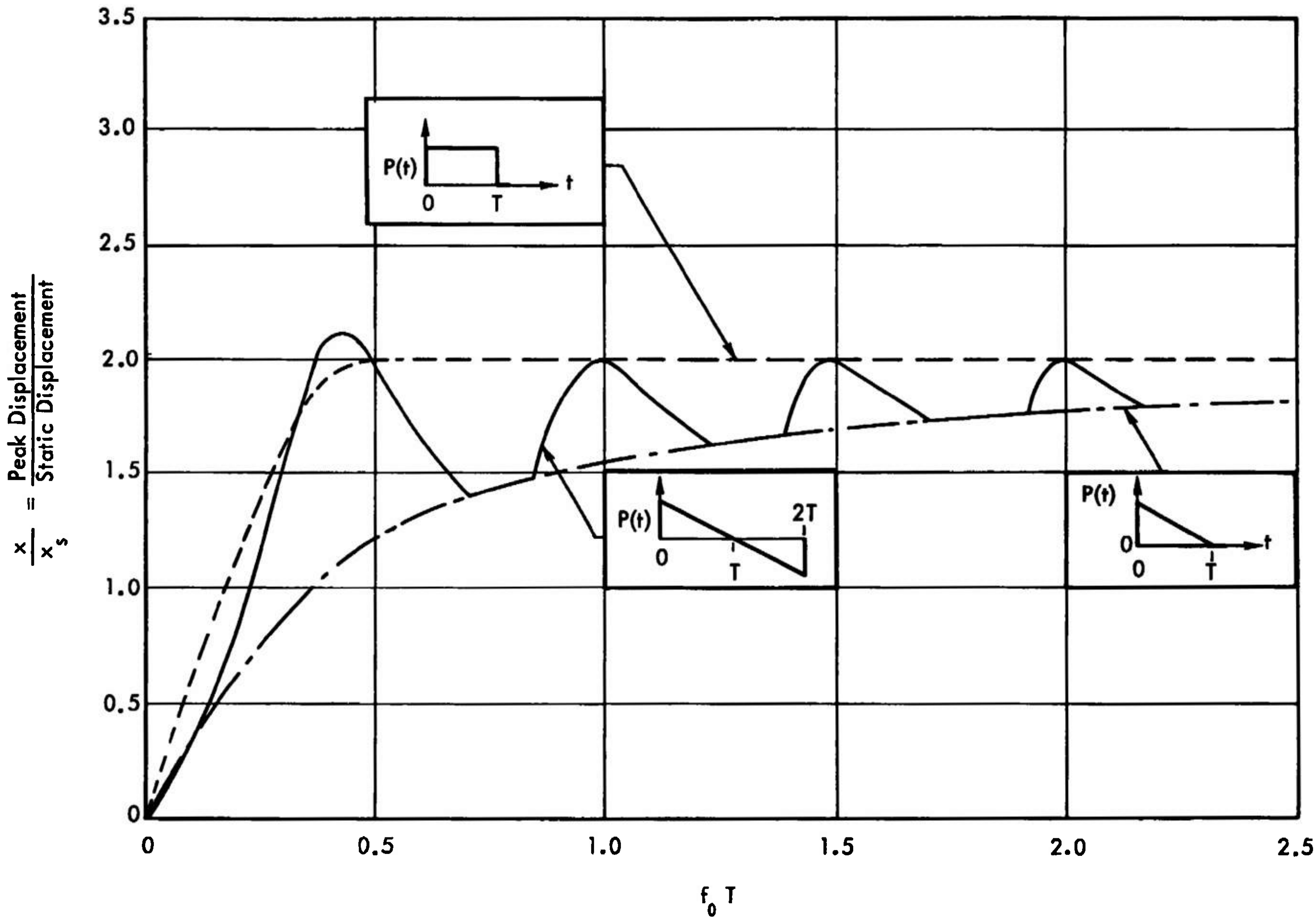


Figure 20. Normalized Displacement Shock Spectra for Excitation of an Undamped Mass-Spring System; Sonic Boom N-Wave, Triangular Pulse and Rectangular Pulse Excitation

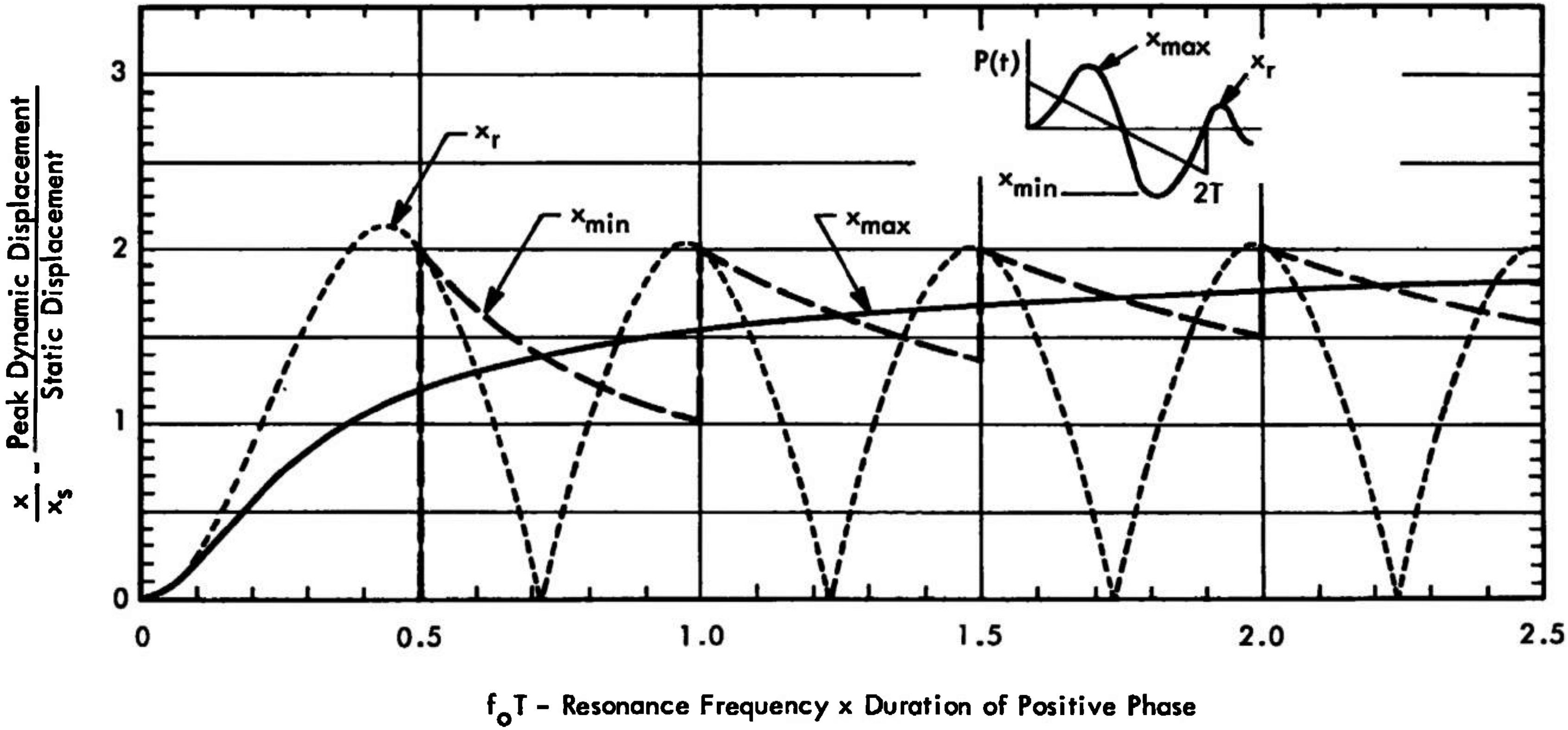


Figure 21. Normalized Displacement Shock Spectrum for Ideal Sonic Boom N-Wave Excitation of Undamped Mass-Spring System

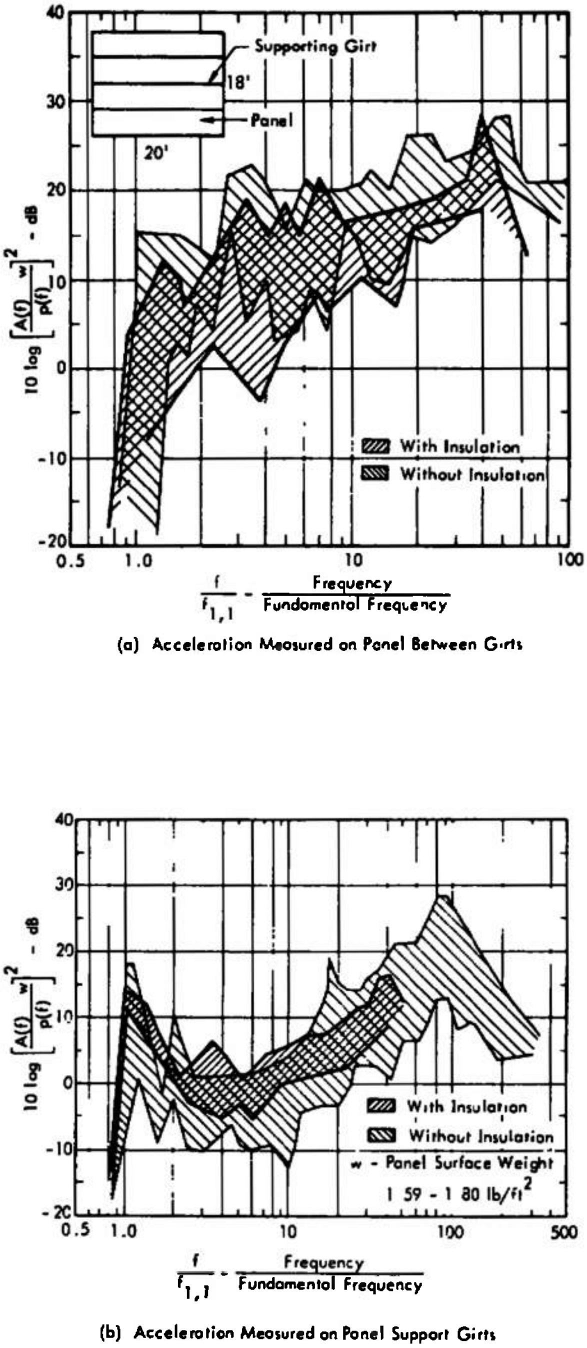


Figure 22. Measured Acoustic Mobility for 20 ft by 18 ft, 26-Gauge Corrugated Steel Walls (Reference 72)

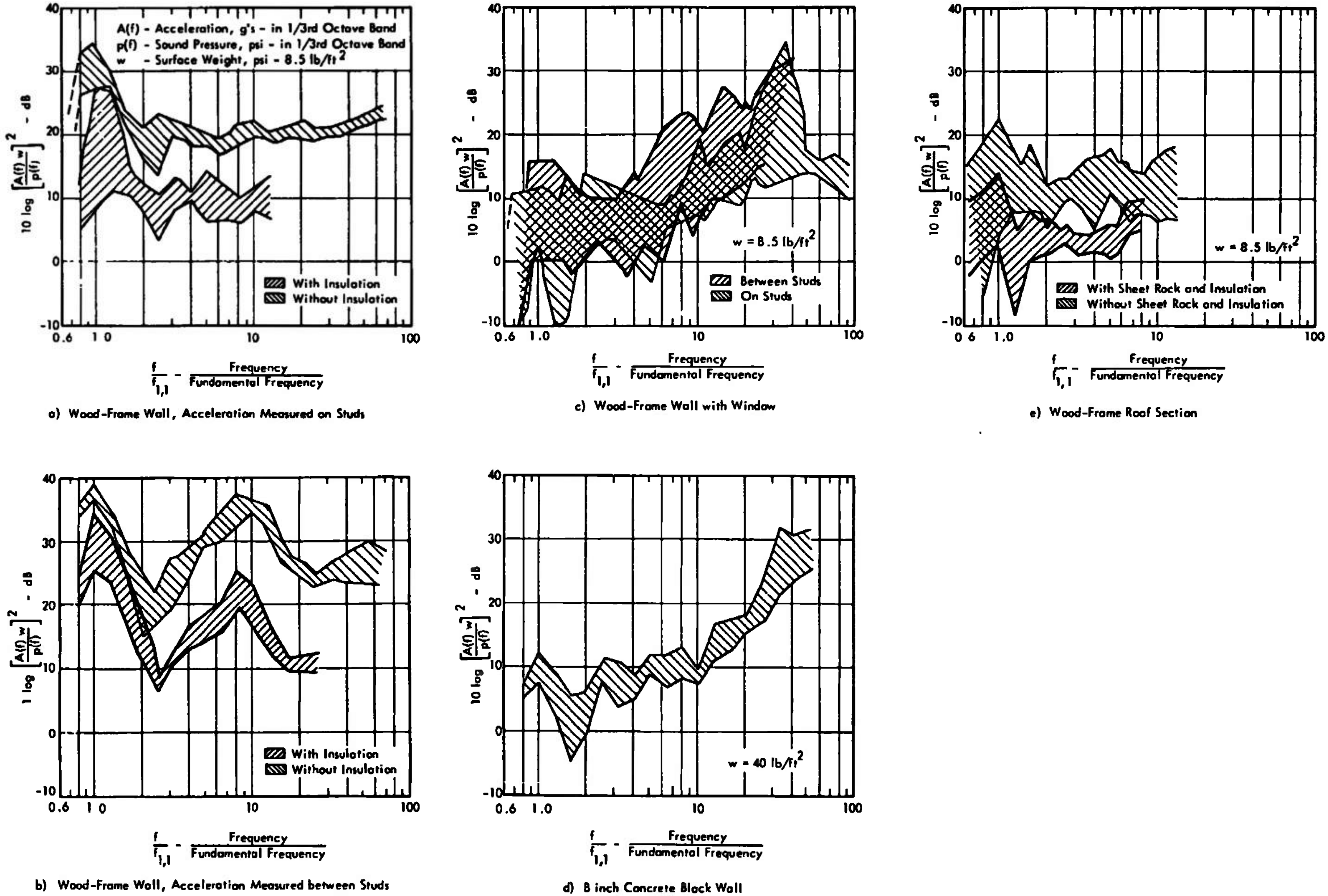


Figure 23. Envelope of Measured Acoustic Mobility for Residential Walls (Reference 72)

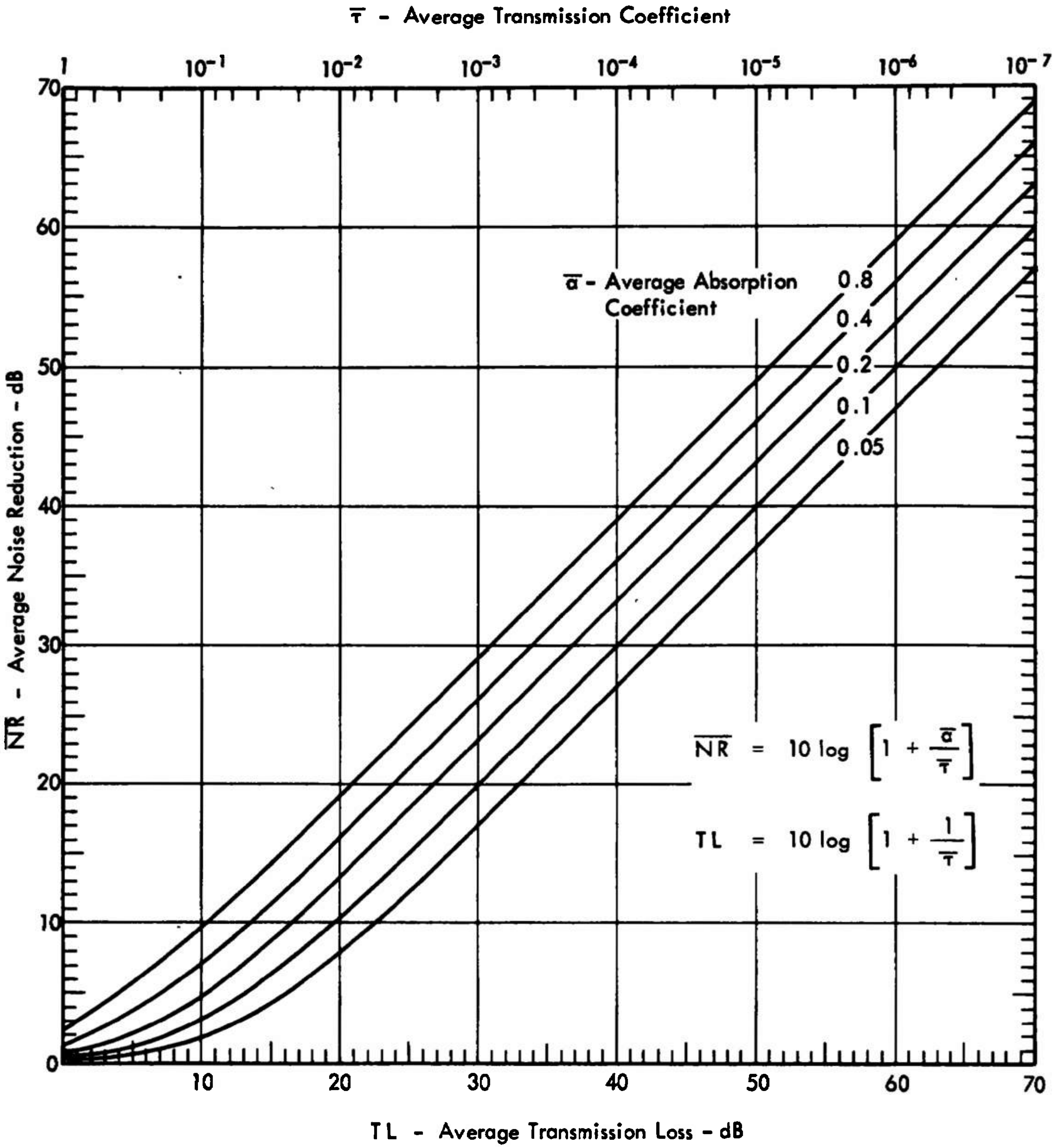


Figure 24. Noise Reduction Versus Absorption Coefficient and Either Average Transmission Coefficient or Average Transmission Loss of Building Walls

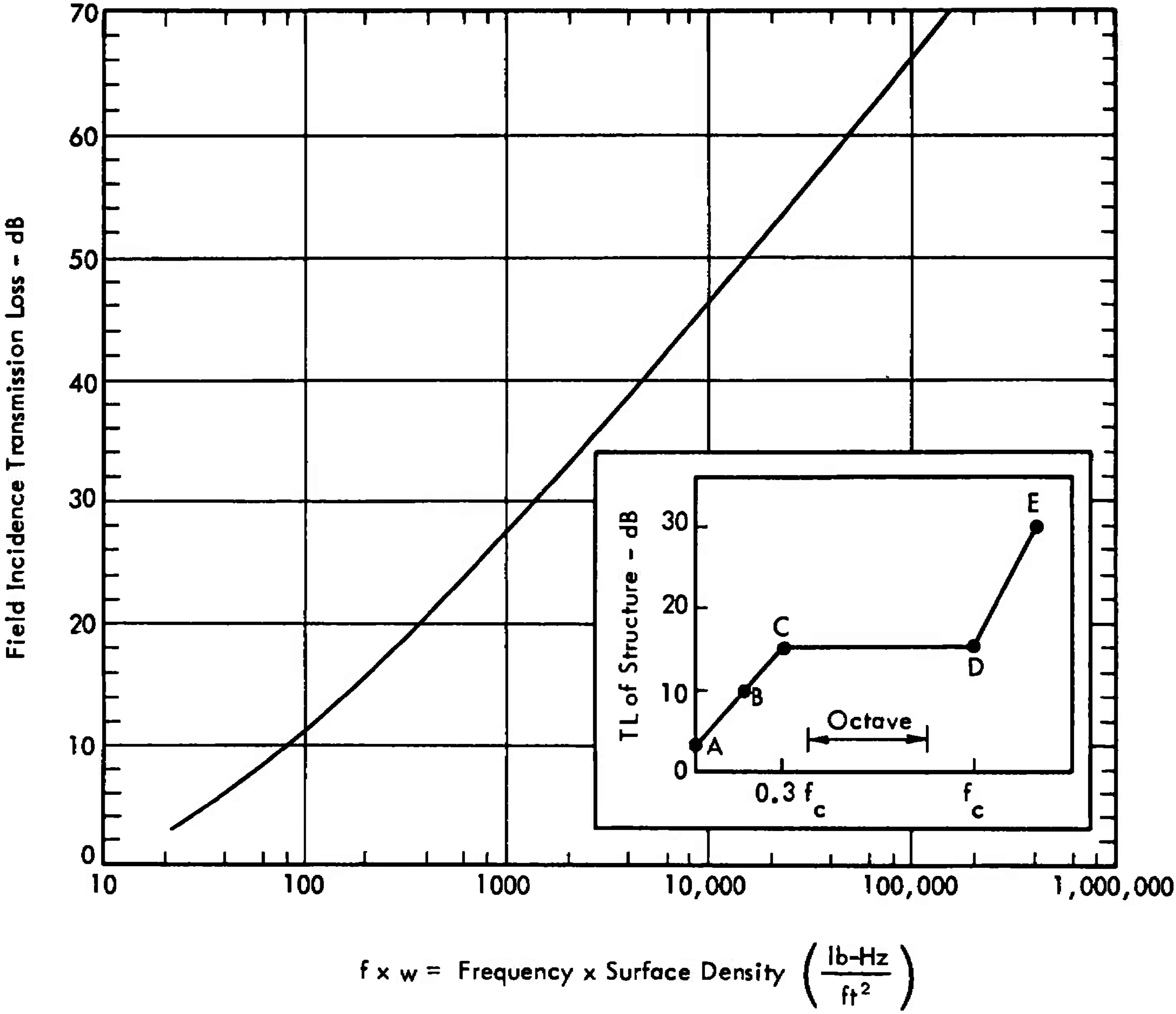
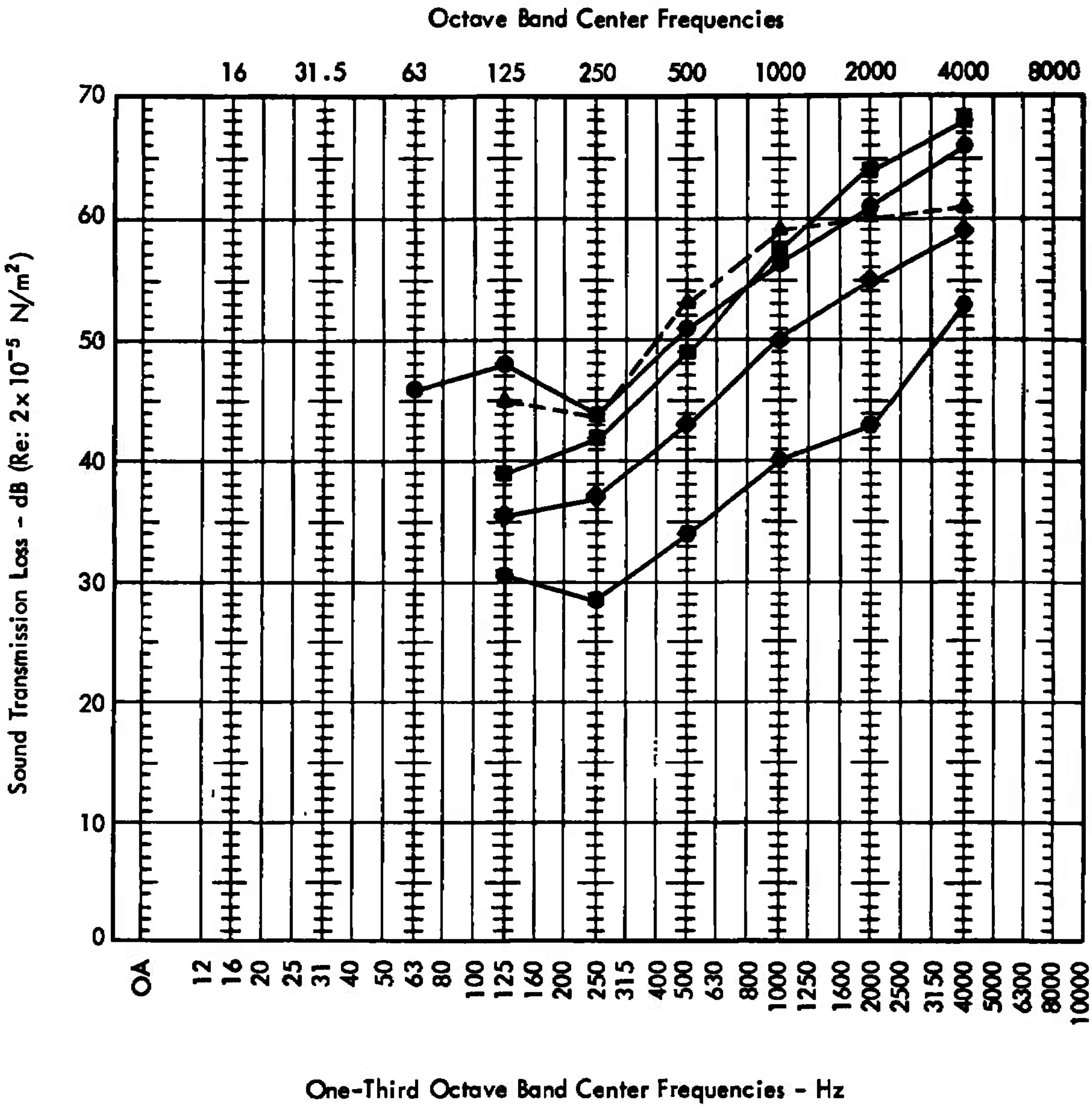


Figure 25. Field Incidence Transmission Loss of Panels and Design Chart for Estimating Transmission Loss through a Structure



- ● 7/8 in.Gypsum Plaster on Expanded Metal Lath on Both Sides of 3-1/4 in. Metal Studs, 16 in. o.c. Total Thickness 5 in. Surface Density 19.6 lb/sq ft
- ■ Solid Concrete 6 in. 1/2 in. Plaster on Both Sides. Surface Density 80 lb/ sq ft. (STC = 52 dB)
- ● Concrete Wall, 12 in. (STC = 62 dB)
- ▲ 12 in. Thick. Surface Density 121 lb/ sq ft 57. (STC = 54 dB)
- ◆ 4-1/2 in. Brick, 1/2 in. Plaster on Both Sides. Total Thickness 5-1/2 in. Surface Density 55 lb/sq ft.

Figure 26. Sound Transmission Loss Through Typical Building Elements

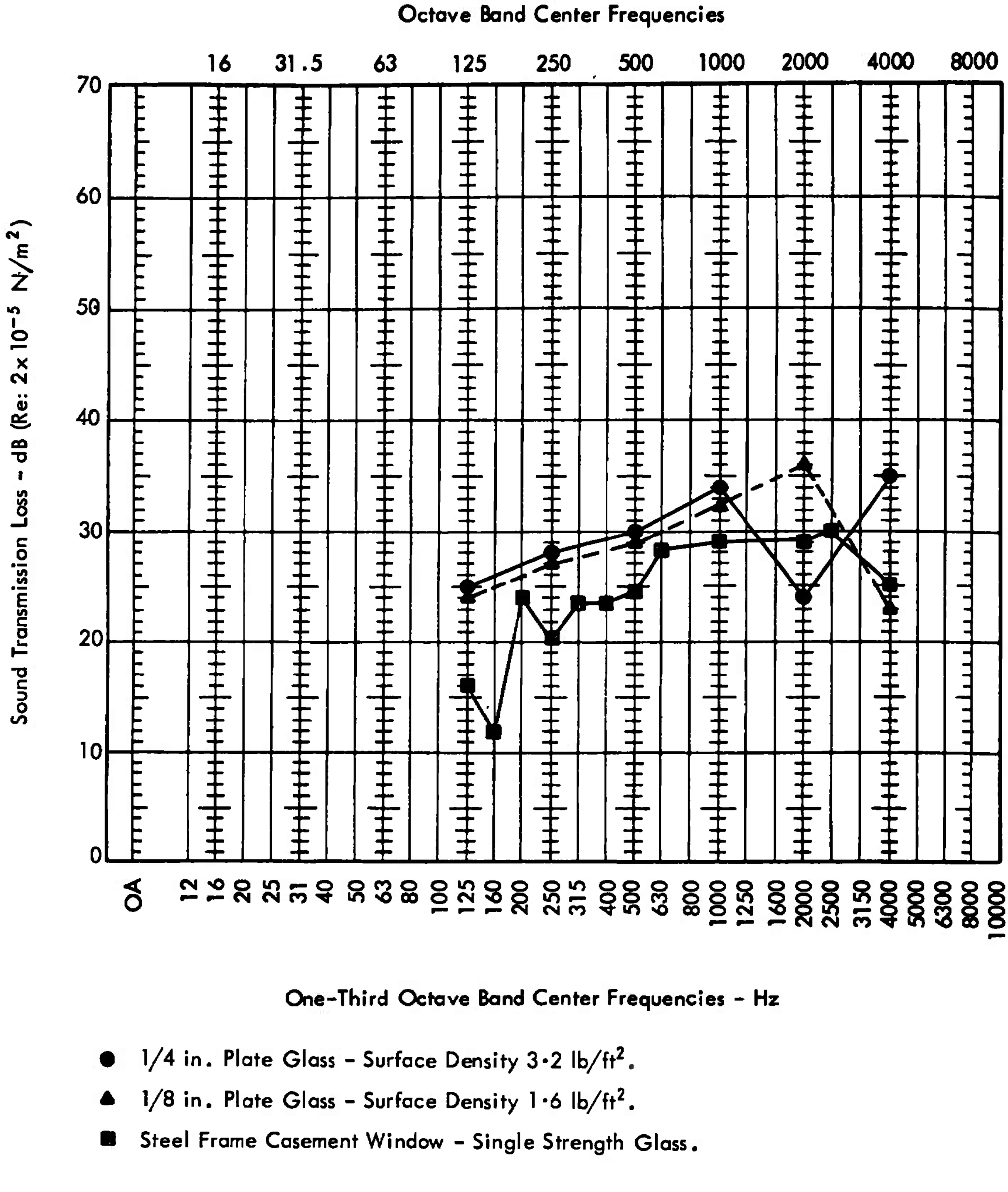
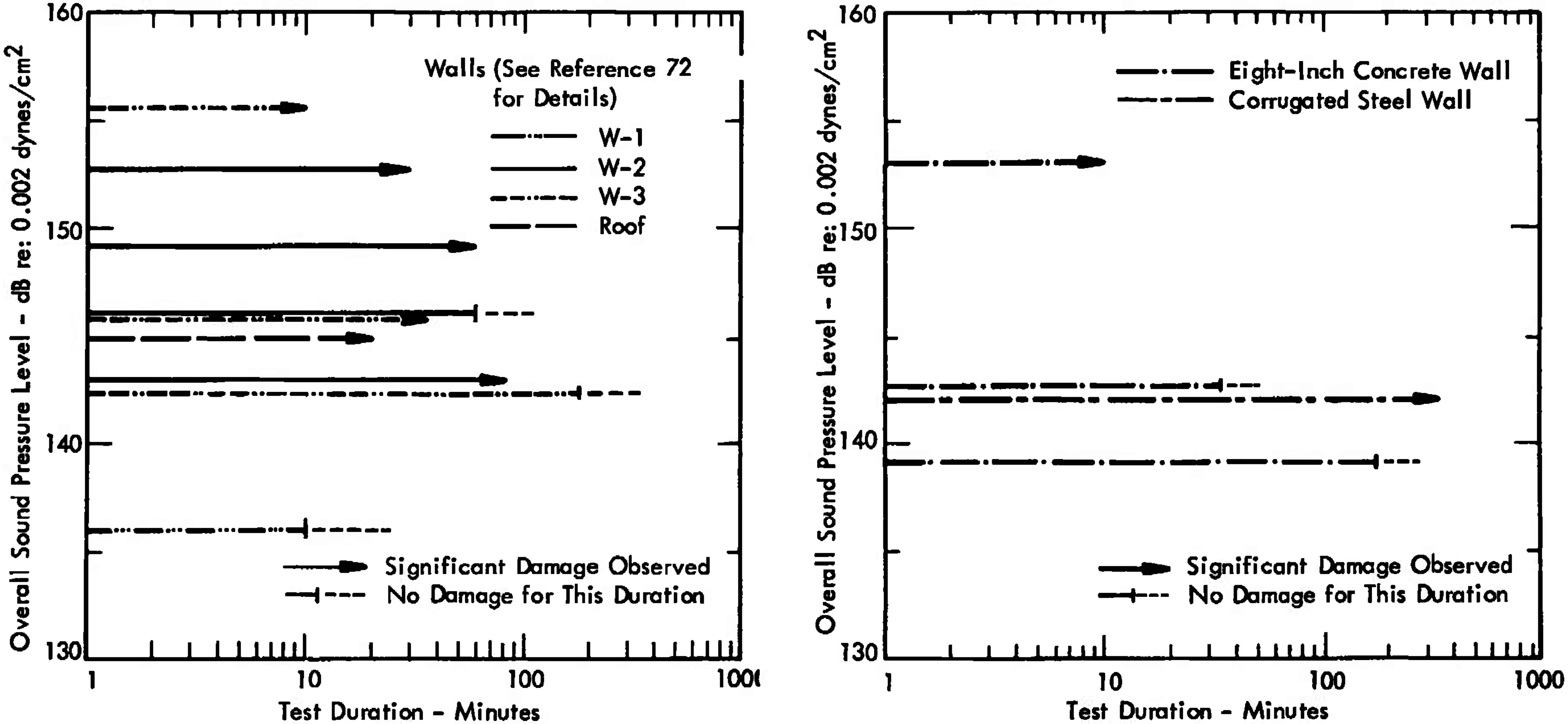


Figure 26. Concluded



(a) Wood-Frame Residential Walls and Roof Section

(b) Eight-Inch Concrete Wall and Steel Industrial Wall

Figure 27. Summary of Fatigue Damage Results from Acoustic Tests of Residential and Steel Industrial Walls (Data from Reference 72)

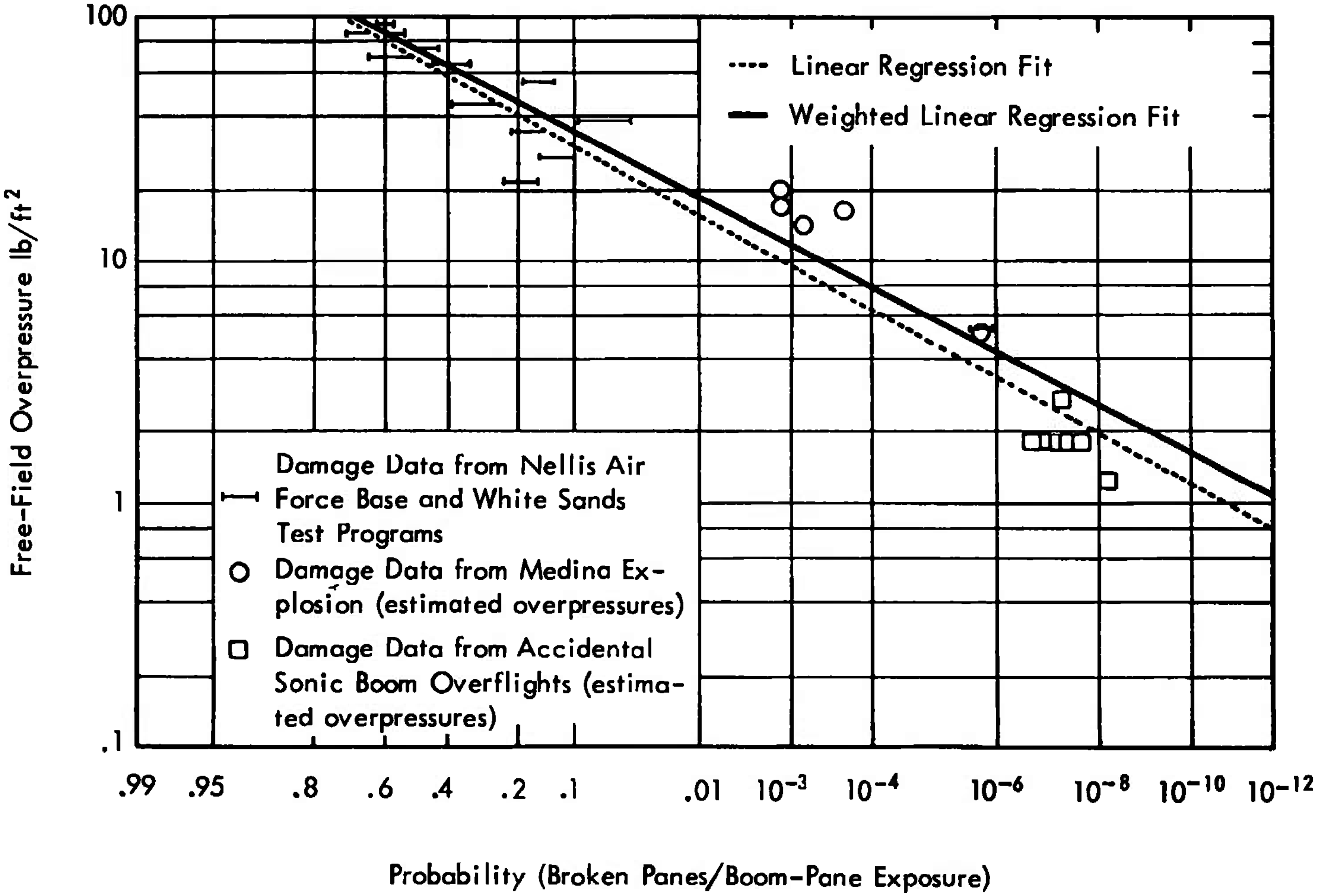


Figure 28. Weighted and Nonweighted Glass Breakage Linear Regression Curves (From Reference 76)

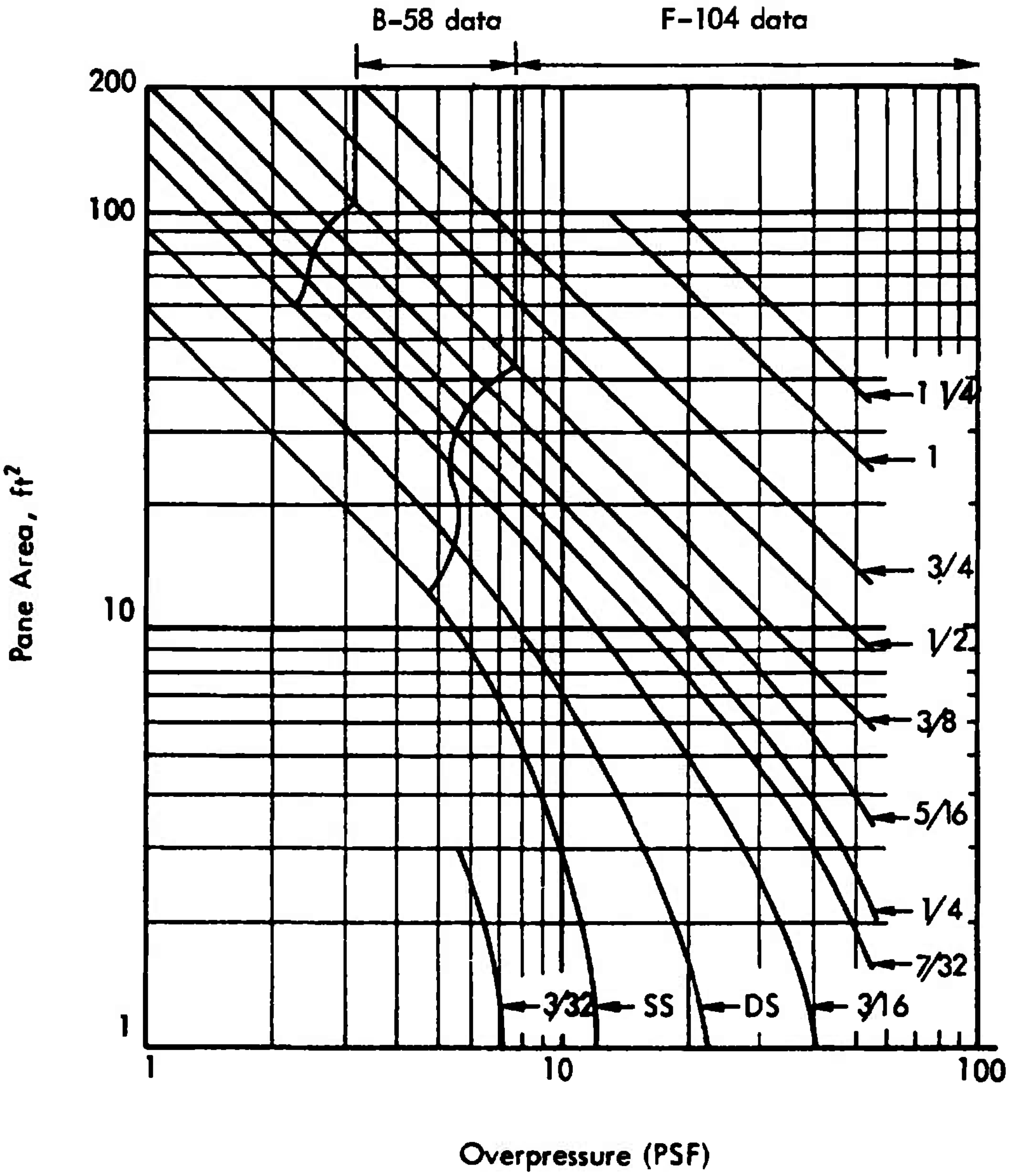
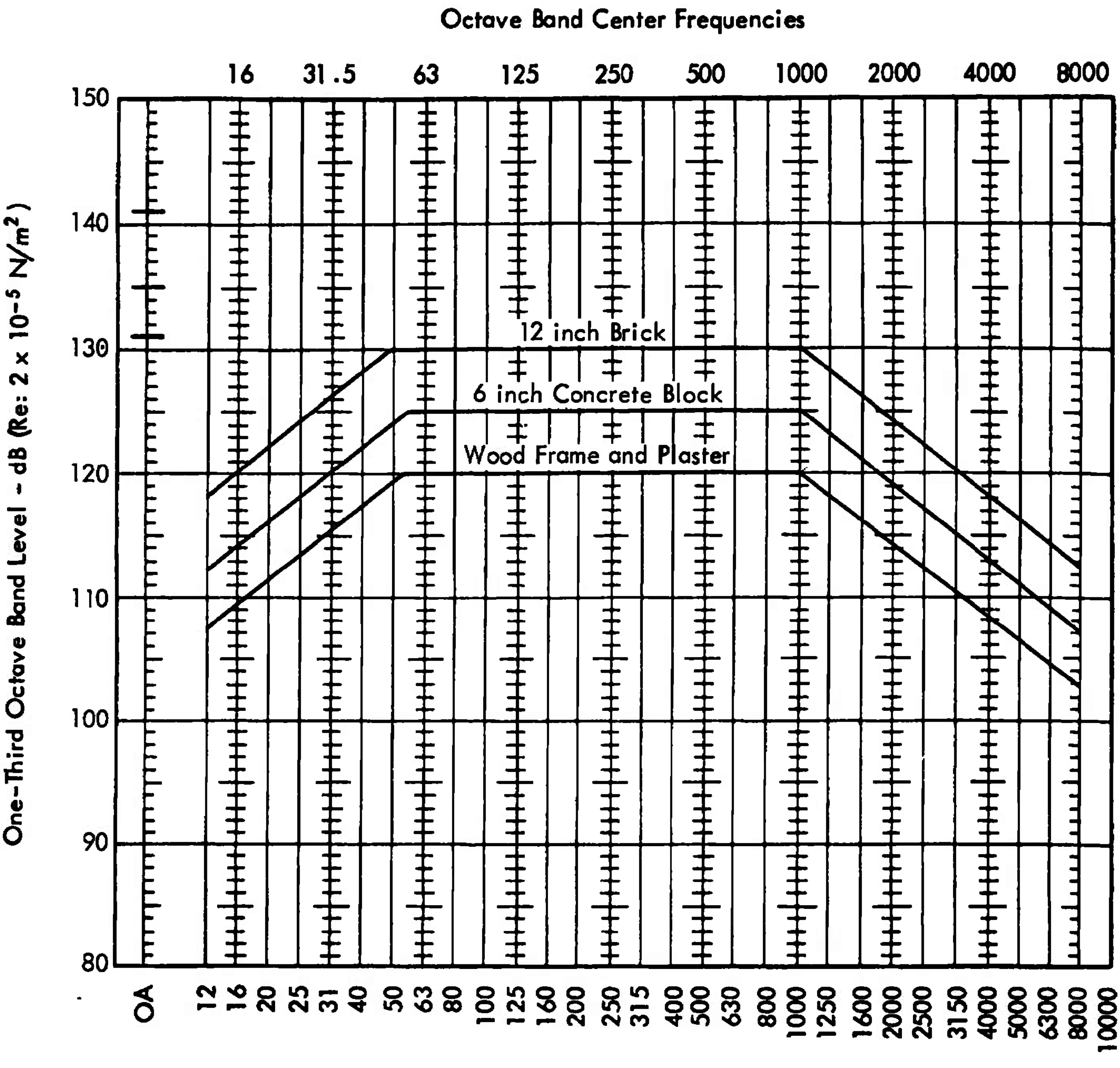


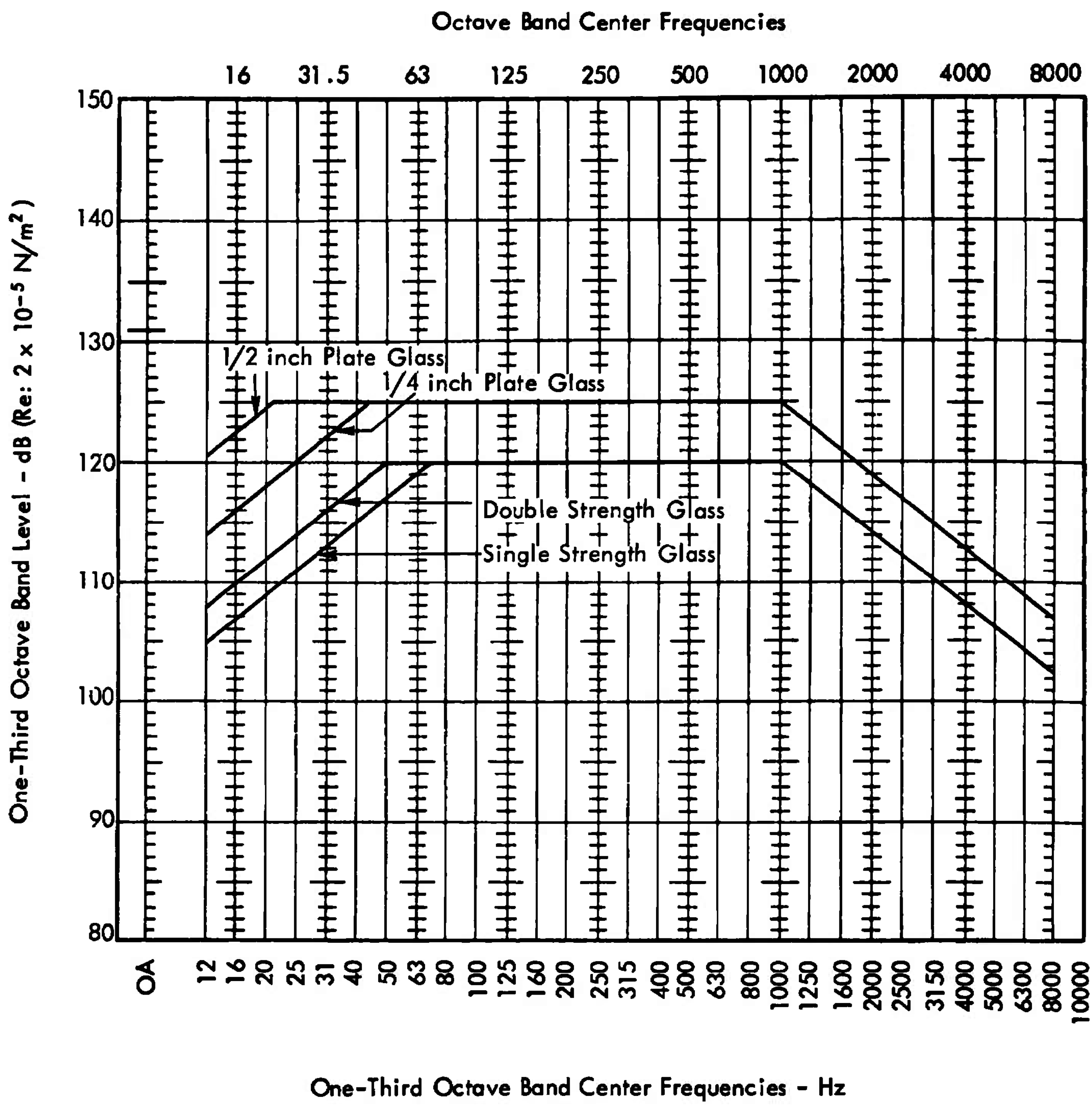
Figure 29. Maximum Safe* Predicted or Measured Average Free-Field Overpressure for Plate and Window Glass (From Reference 76)

* Less than 10^{-5} boom-pane chance of inducing a slight crack in glass pane.



(a) Wall Structure

Figure 30. Acoustic Environment Criteria for Damage to Walls and Windows



(b) Windows

Figure 30. Concluded

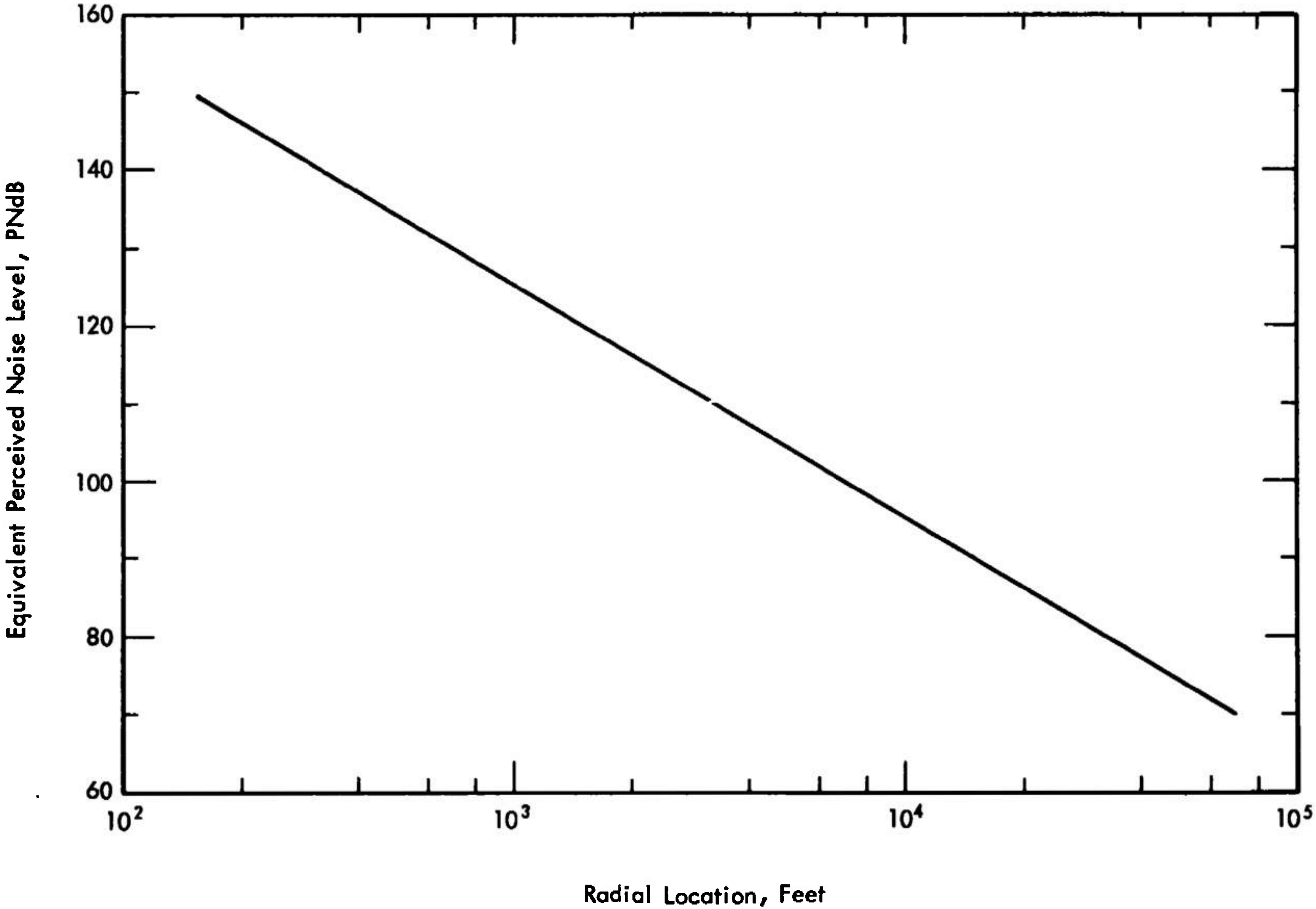


Figure 31. Variation of Equivalent Perceived Noise Level of Starting Shock Wave with Radial Location, Mass Flux of 165,000 lb_m/sec

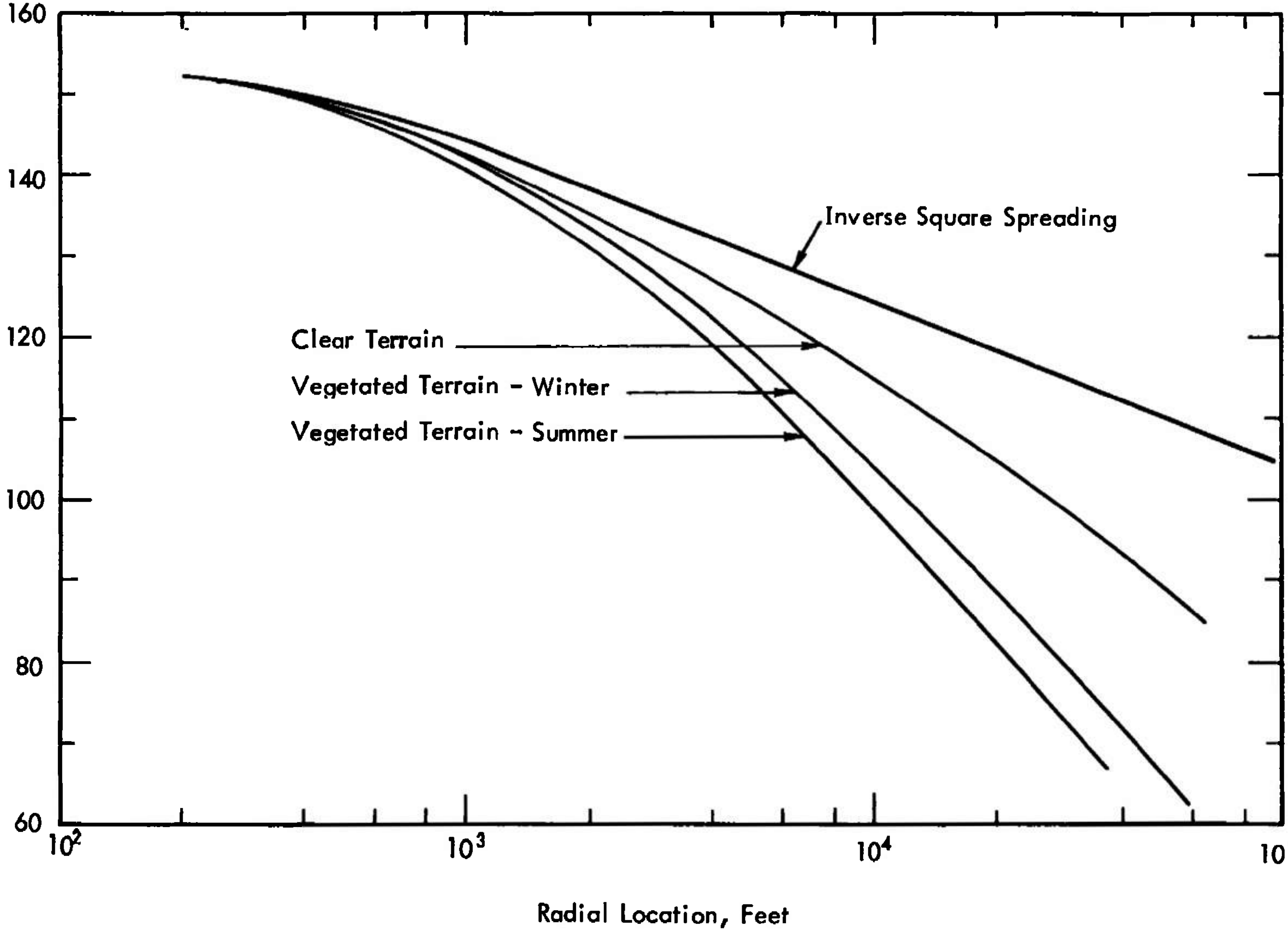


Figure 32. Variation of Perceived Noise Level of Steady State Exhaust Flow Environment with Radial Location, Mass Flux of 165,000 lb_m/sec

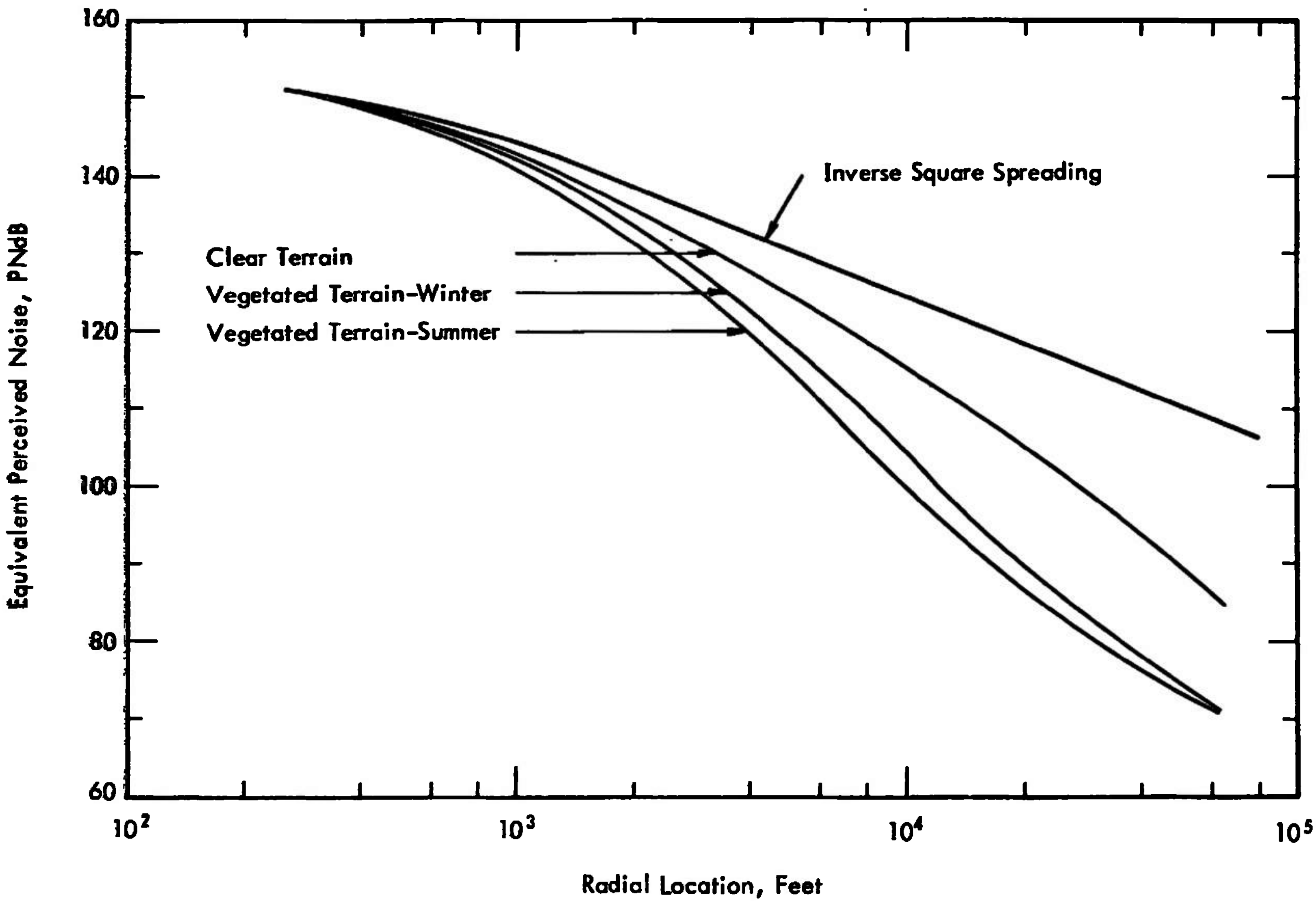


Figure 33. Variation of Perceived Noisiness of Combined Starting Shock and Steady State Exhaust Flow Environment with Radial Location, Mass Flux of 165,000 lb_m/sec

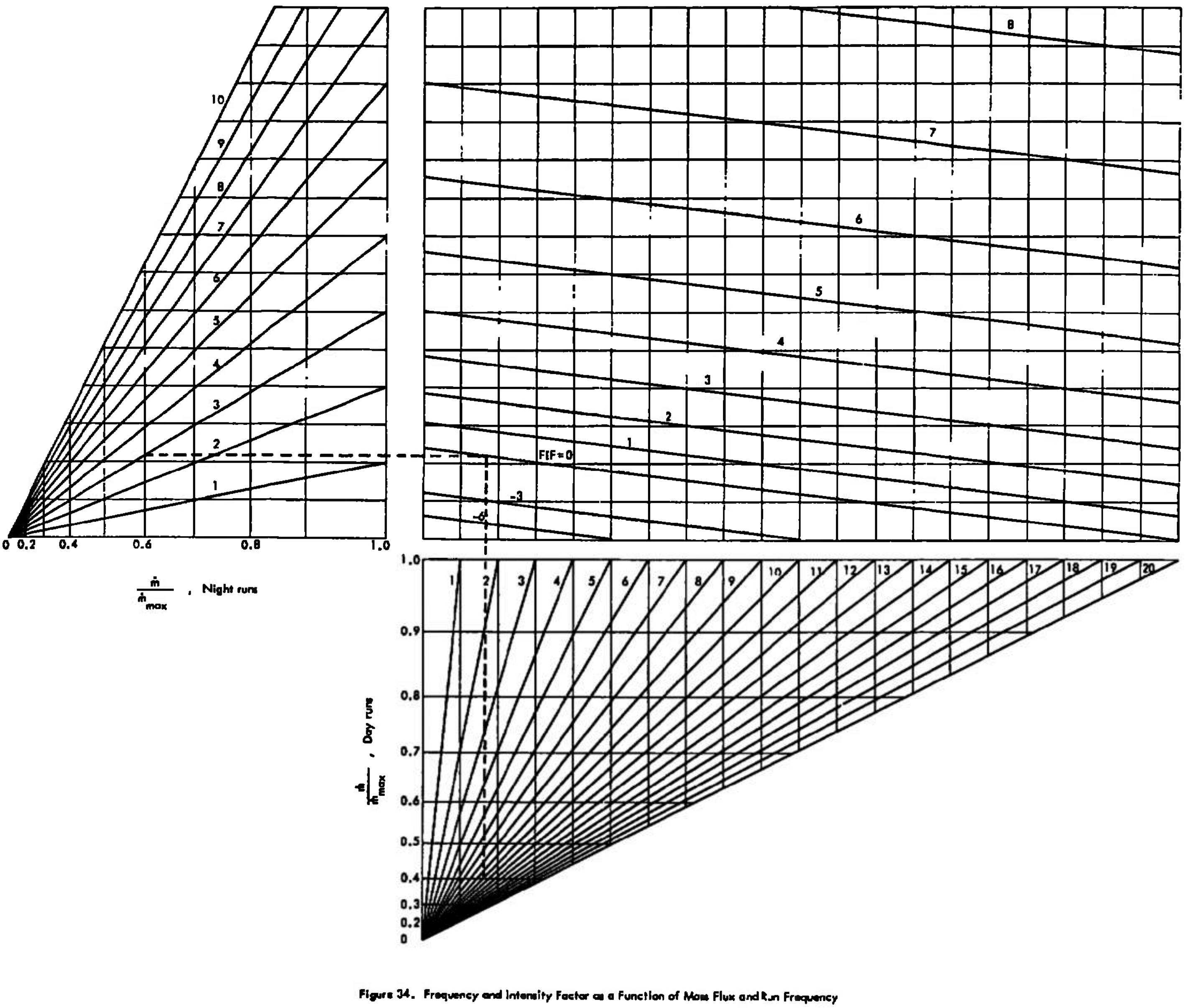


Figure 34. Frequency and Intensity Factor as a Function of Mass Flux and Run Frequency

Example shown is 3 night runs at $\frac{\dot{m}}{\dot{m}_{max}} = .6$, and 10 day runs at $\frac{\dot{m}}{\dot{m}_{max}} = .4$, for which FIF = 0

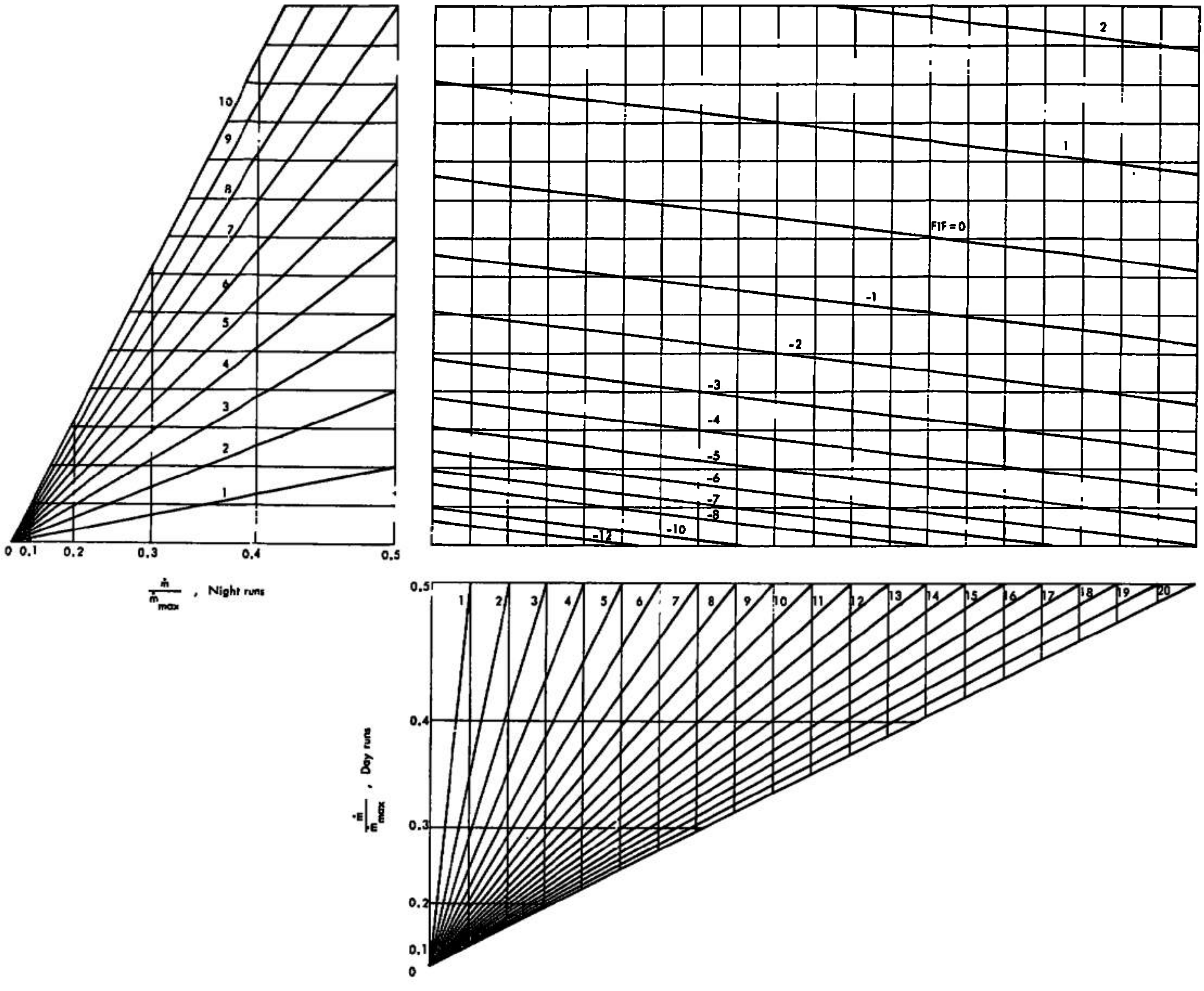


Figure 35. Frequency and Intensity Factor for $\frac{\dot{m}}{\dot{m}_{max}} \leq .5$

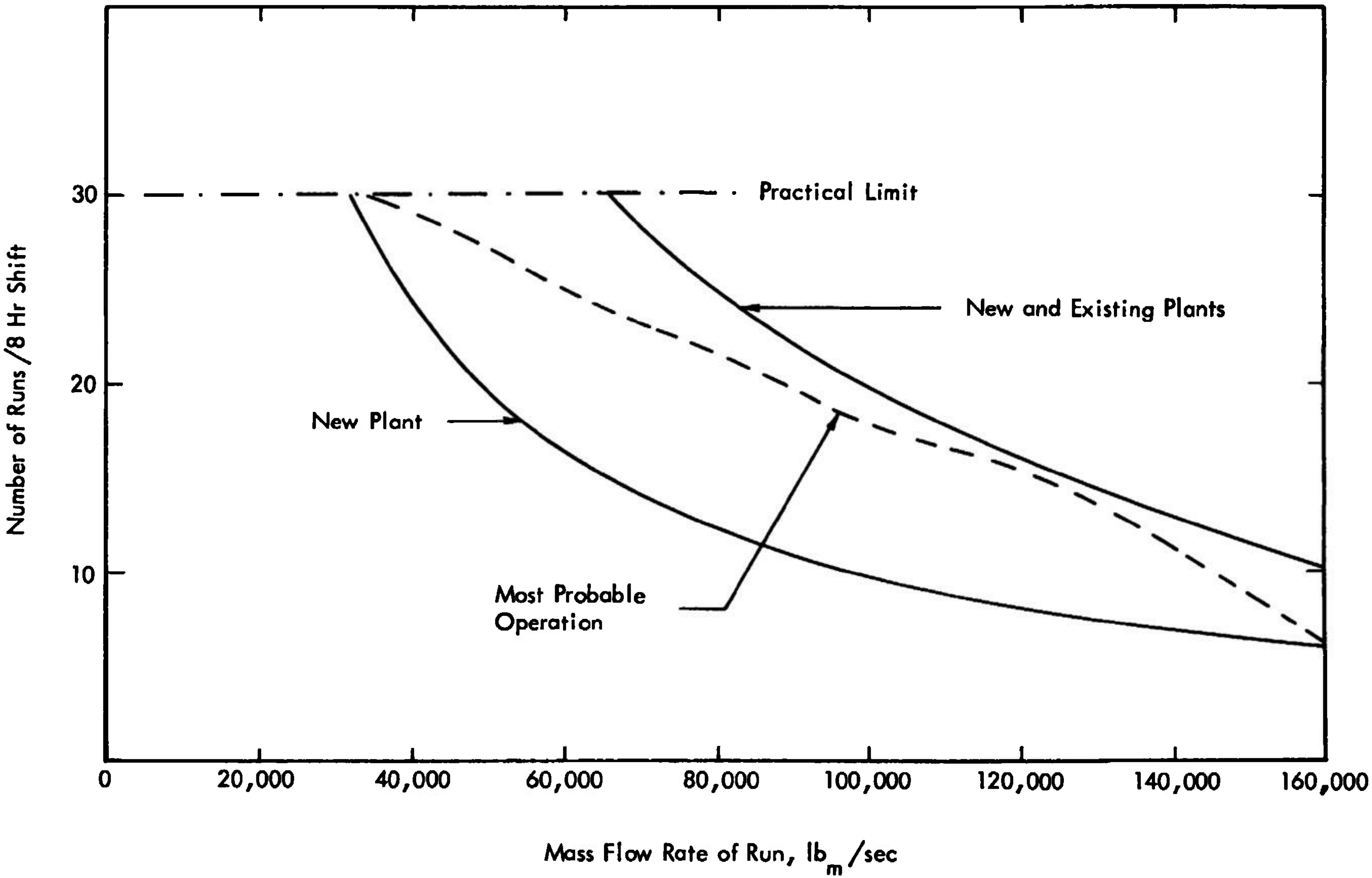


Figure 36. Expected Run Capability of HIRT as a Function of Mass Flux (Reference 81)

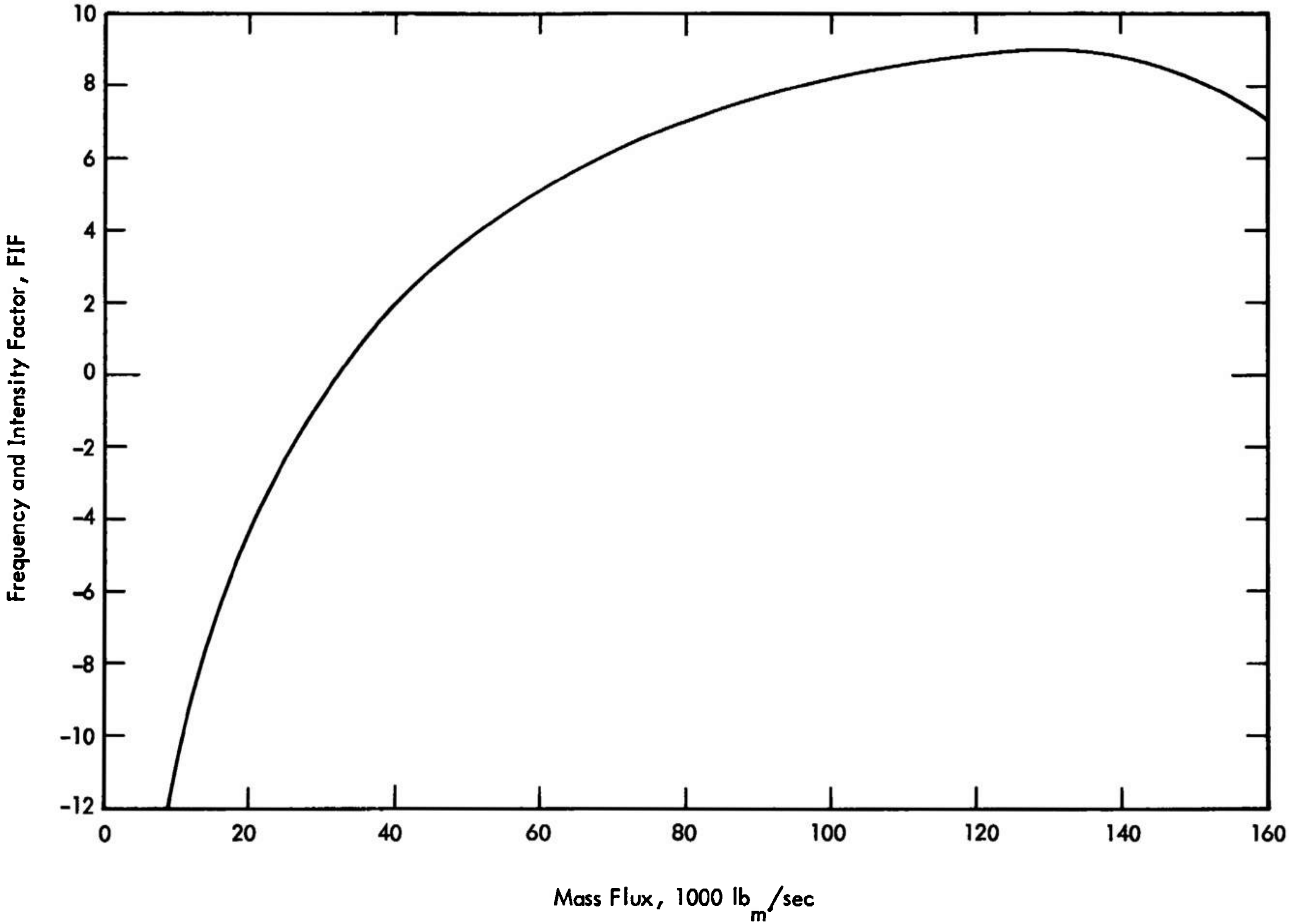


Figure 37. Variation of Frequency and Intensity Factor with Mass Flux for Expected HIRT Capability

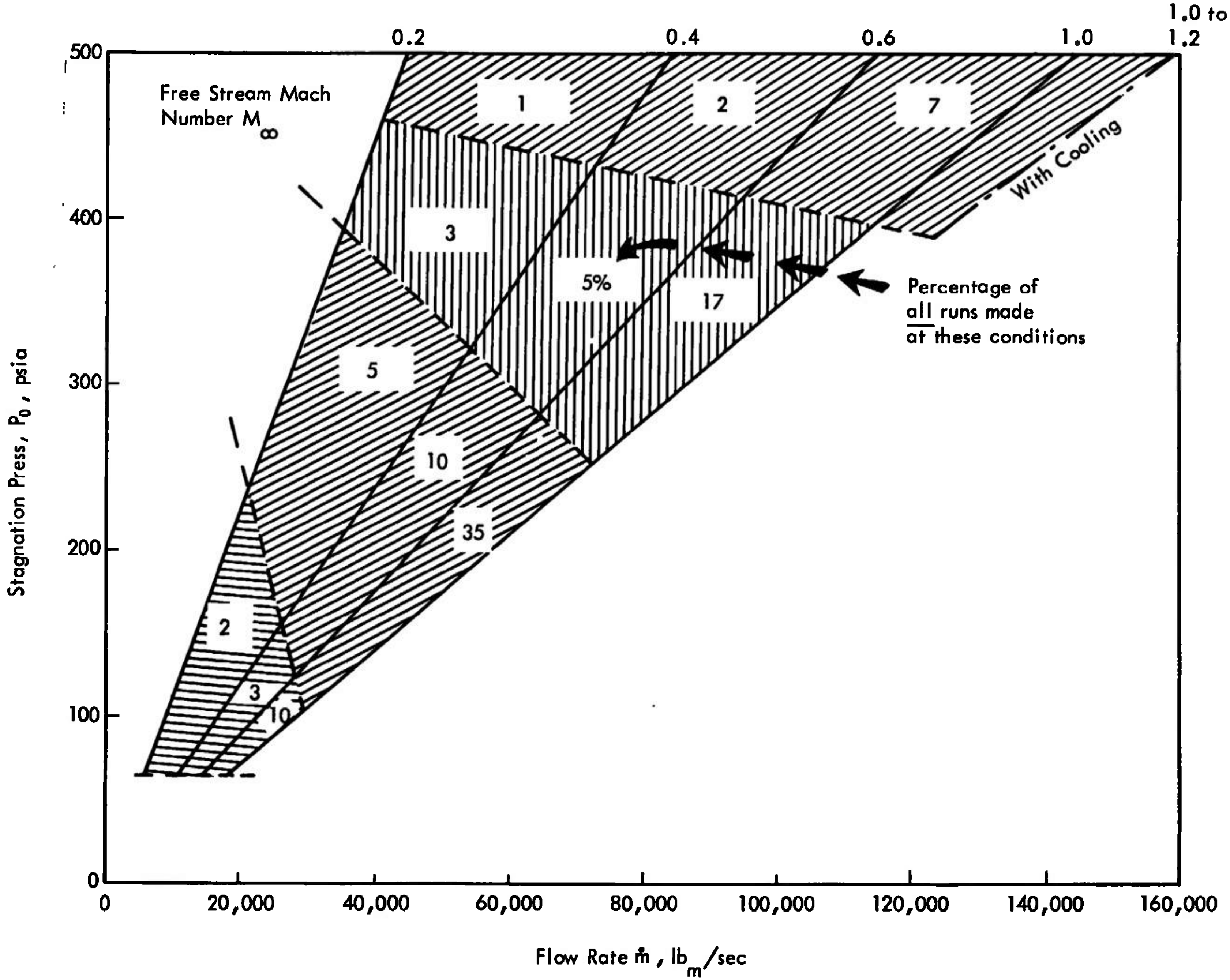


Figure 38. Projected Utilization of HIRT (Reference 81)

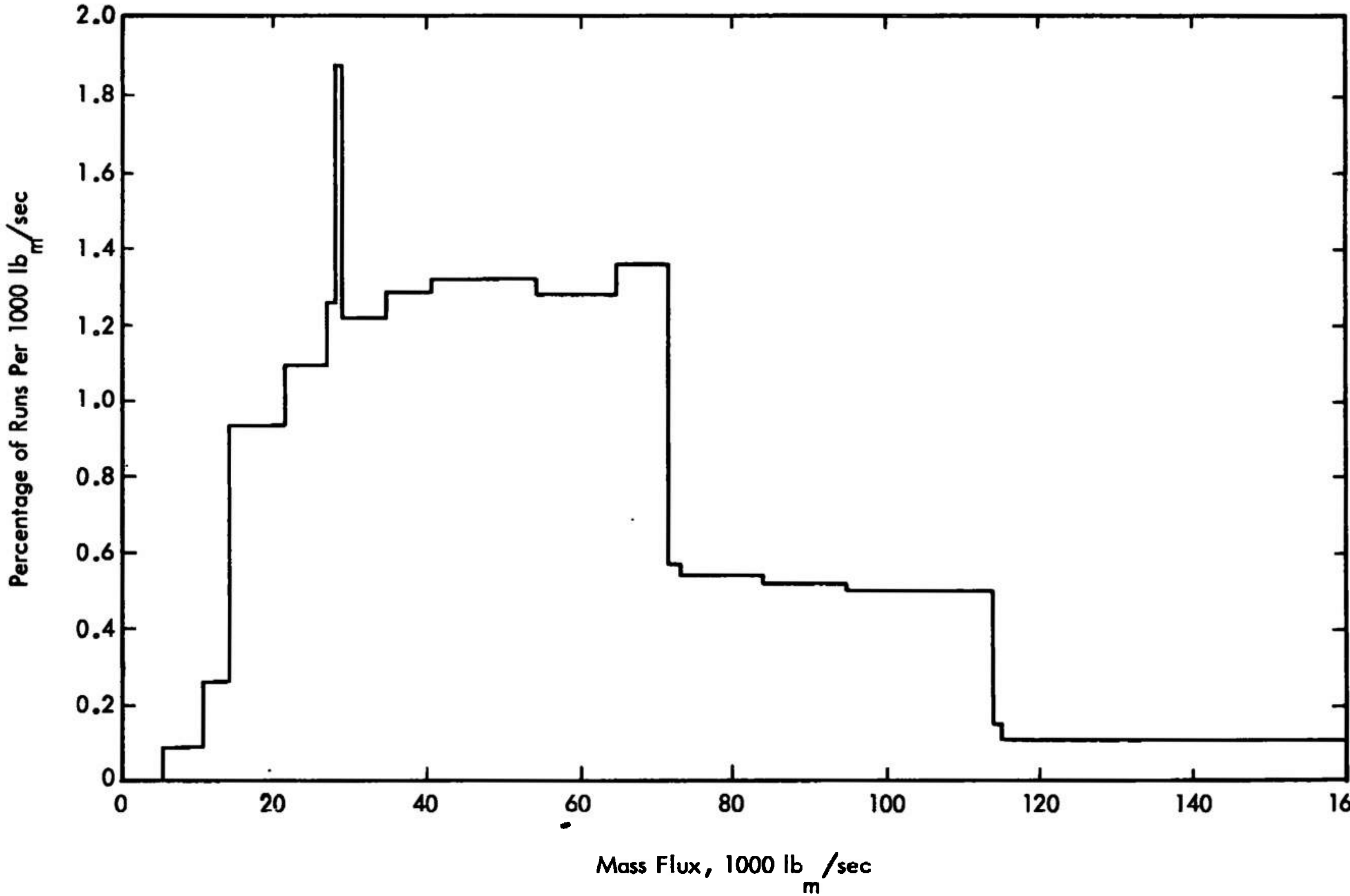


Figure 39. Mass Flux Distribution of Projected HIRT Utilization

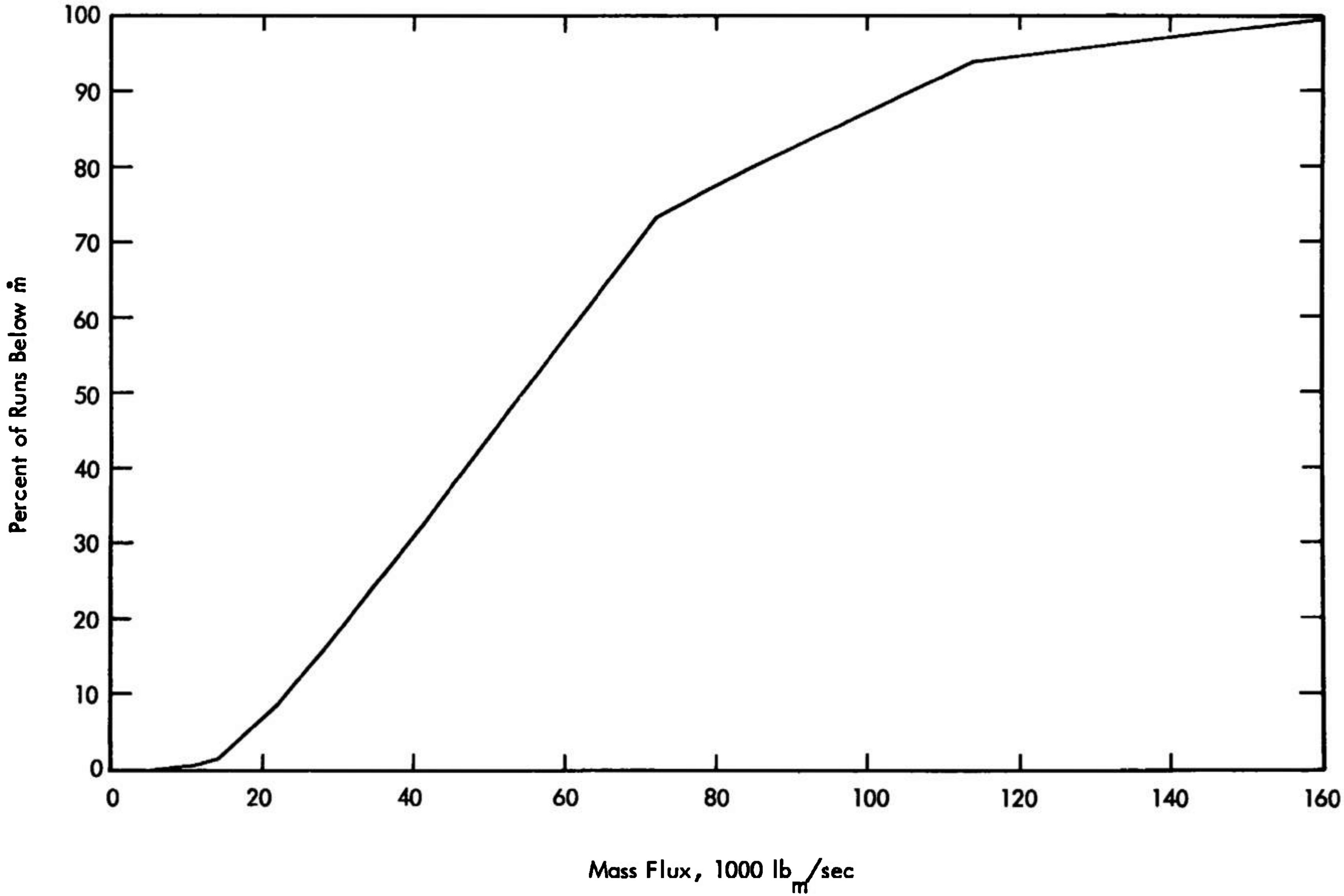


Figure 40. Integrated Mass Flux Distribution of HIRT Utilization

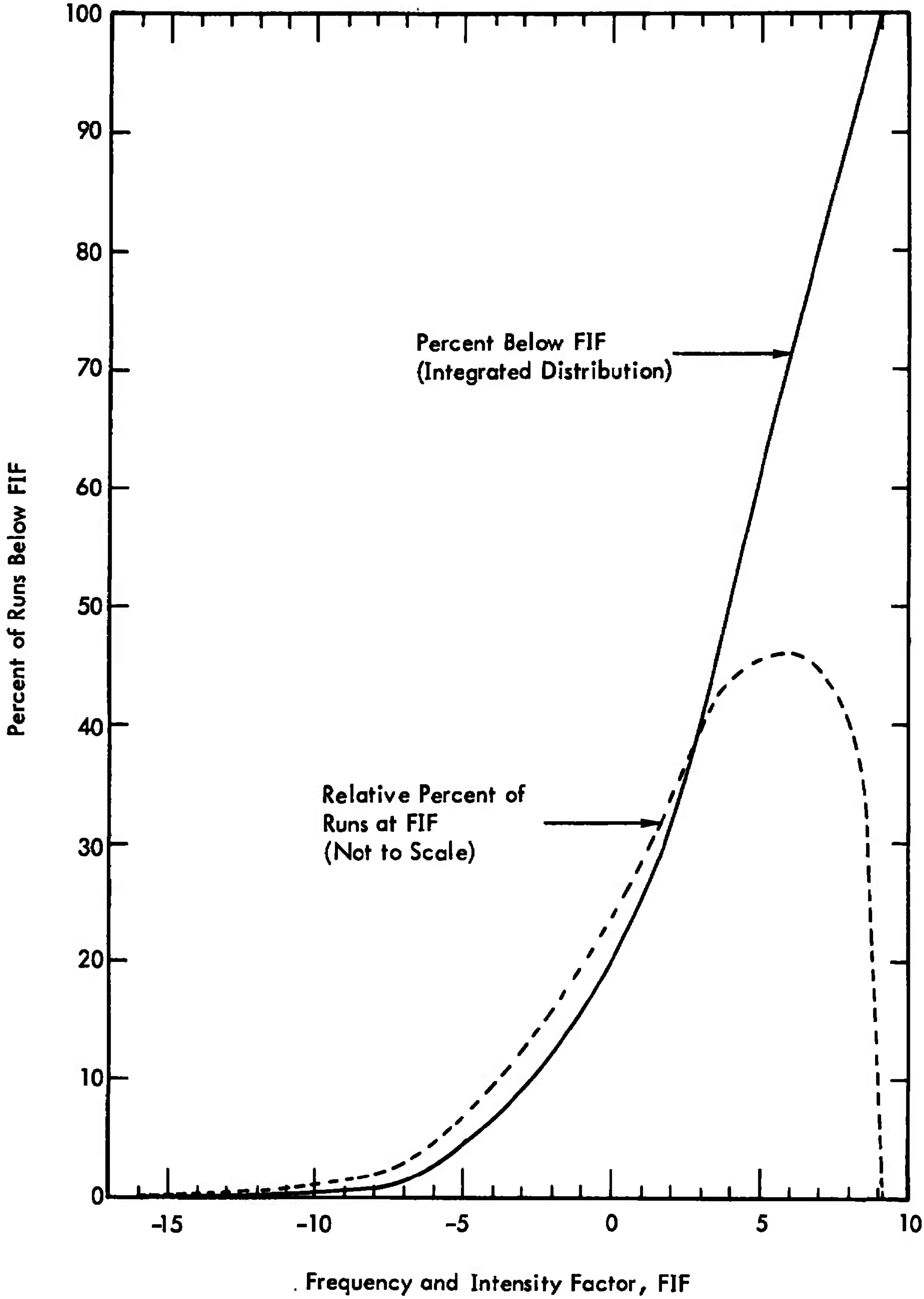


Figure 41. Frequency and Intensity Factor Distribution of Projected HIRT Utilization

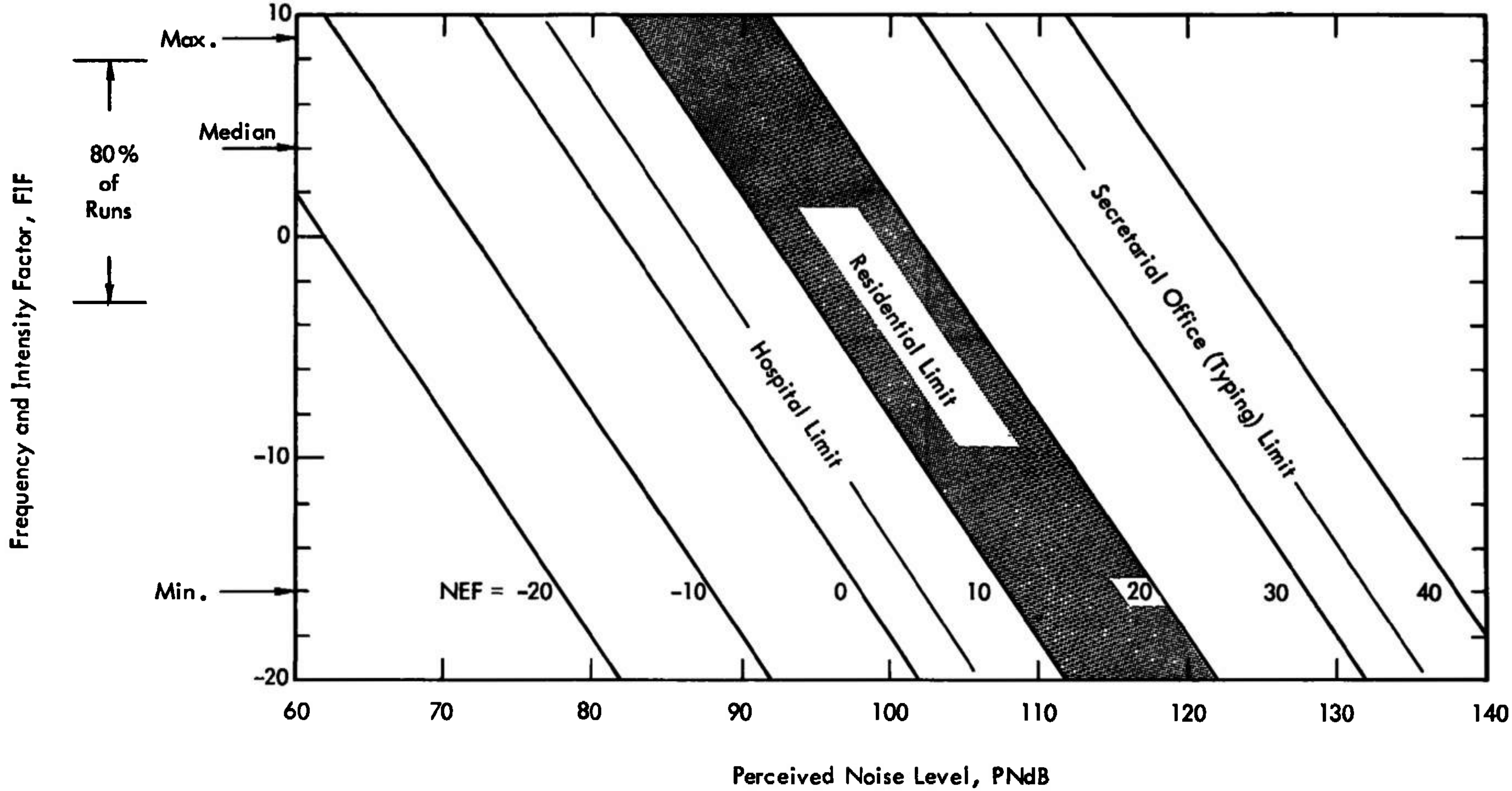


Figure 42. Noise Exposure Forecast as a Function of FIF and Perceived Noise Level at Maximum Mass Flux

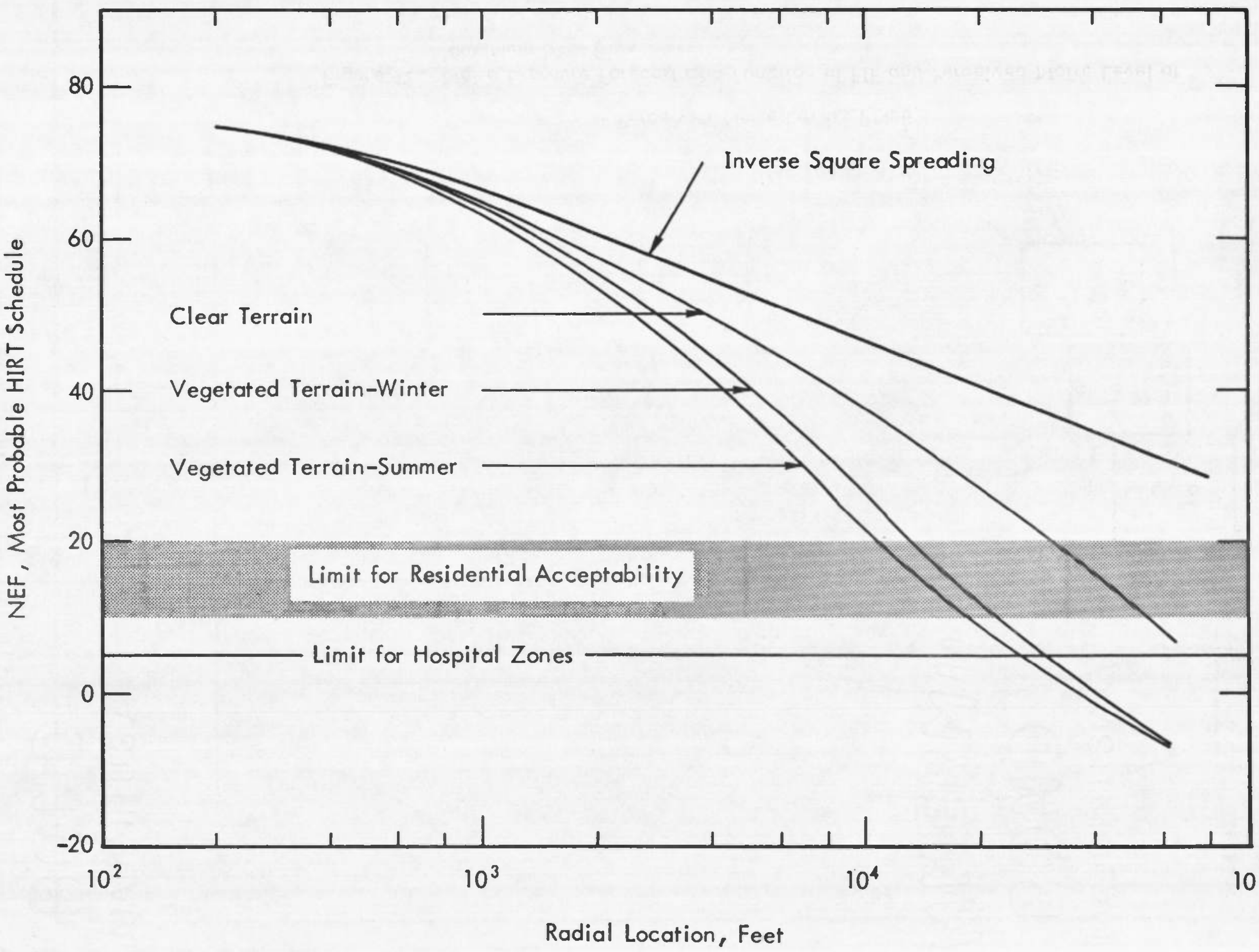


Figure 43. Variation of Noise Exposure Forecast with Radial Location for Expected HIRT Utilization

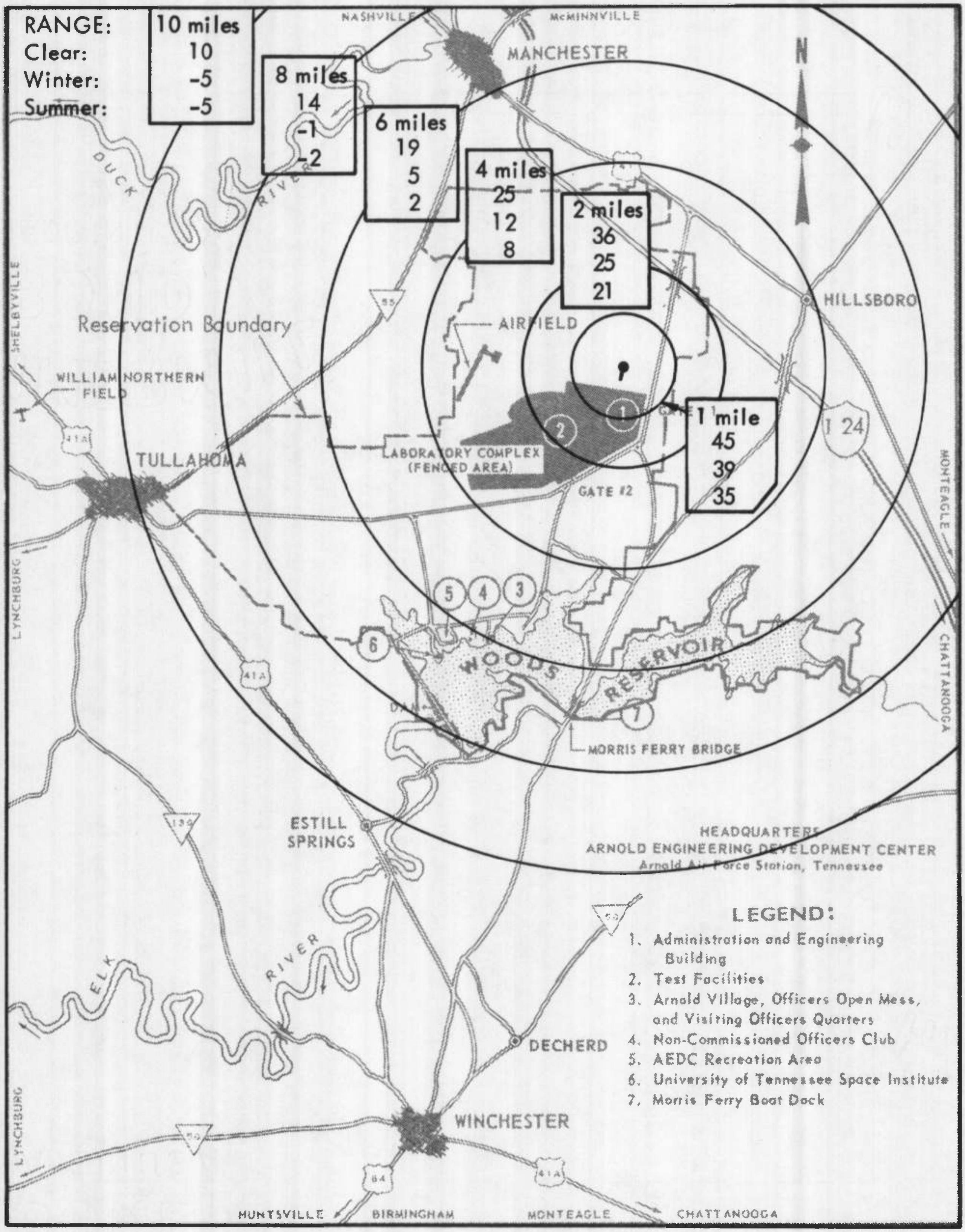


Figure 44. Contours of Constant Noise Exposure Forecast for AEDC Vicinity

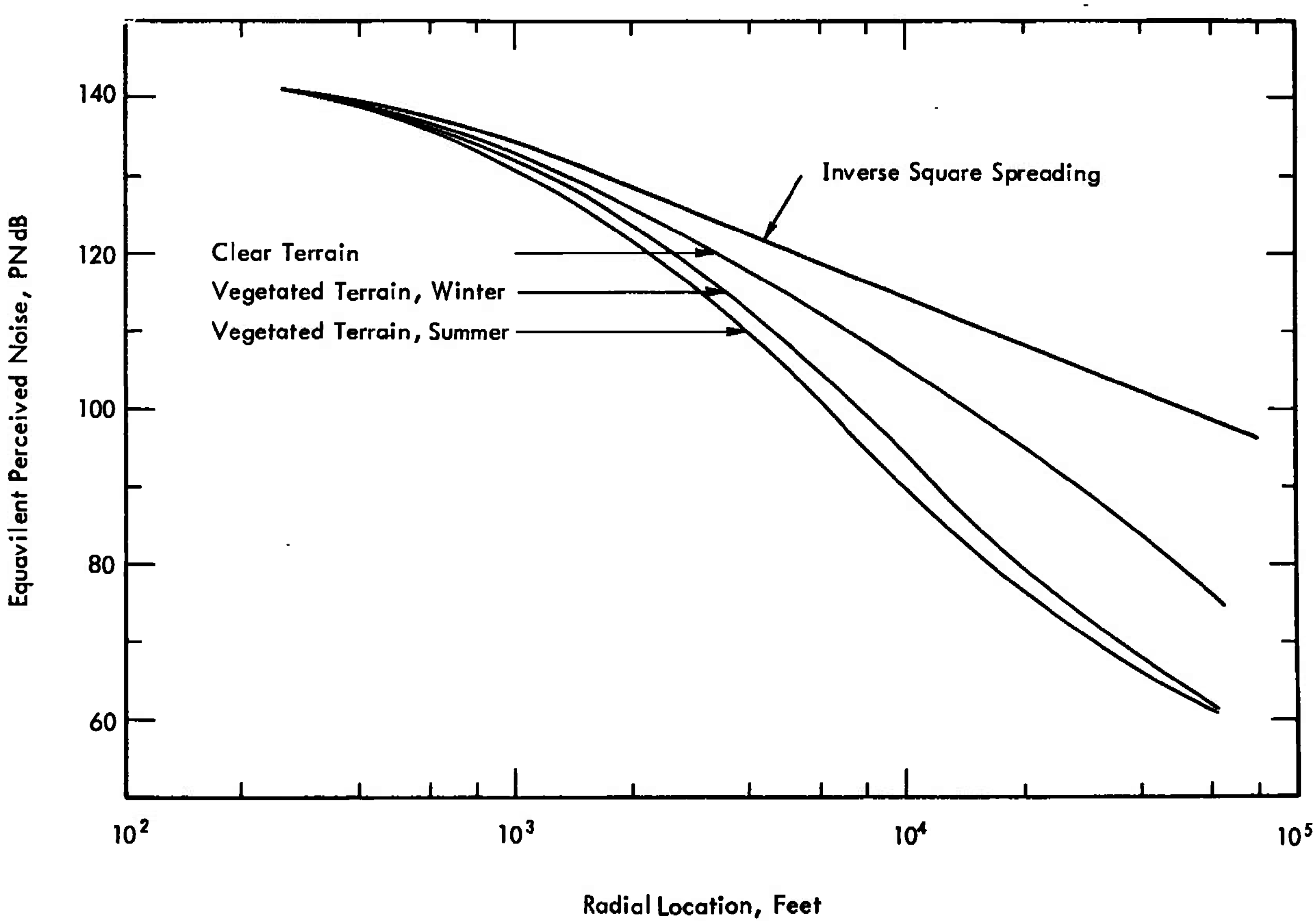


Figure 45. Variation of Perceived Noise Level with Radial Location, Mass Flux of 55,000 lb_m/sec

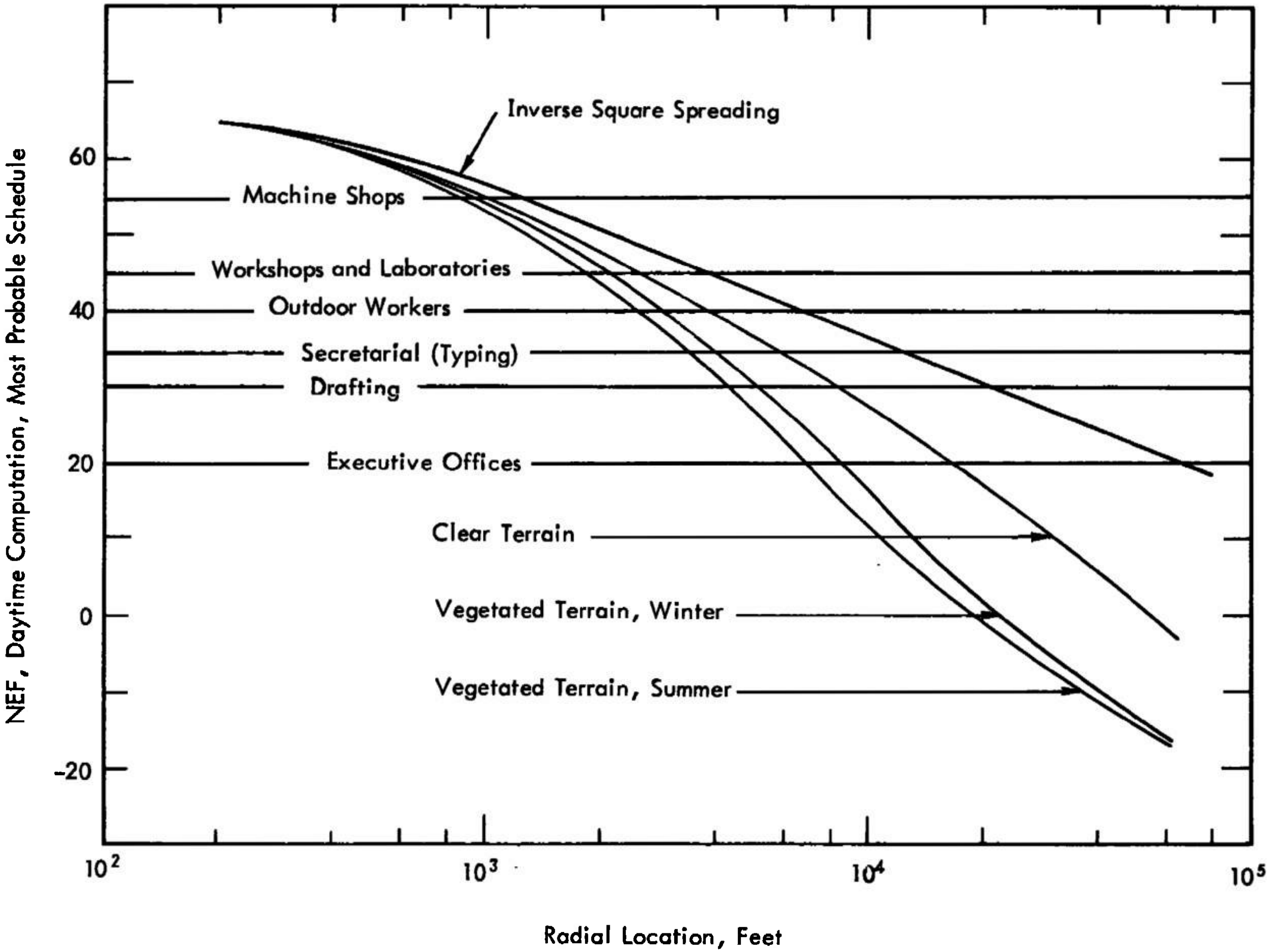


Figure 46. Variation of Noise Exposure Forecast with Radial Location for Expected HIRT Utilization, Daytime Calculation

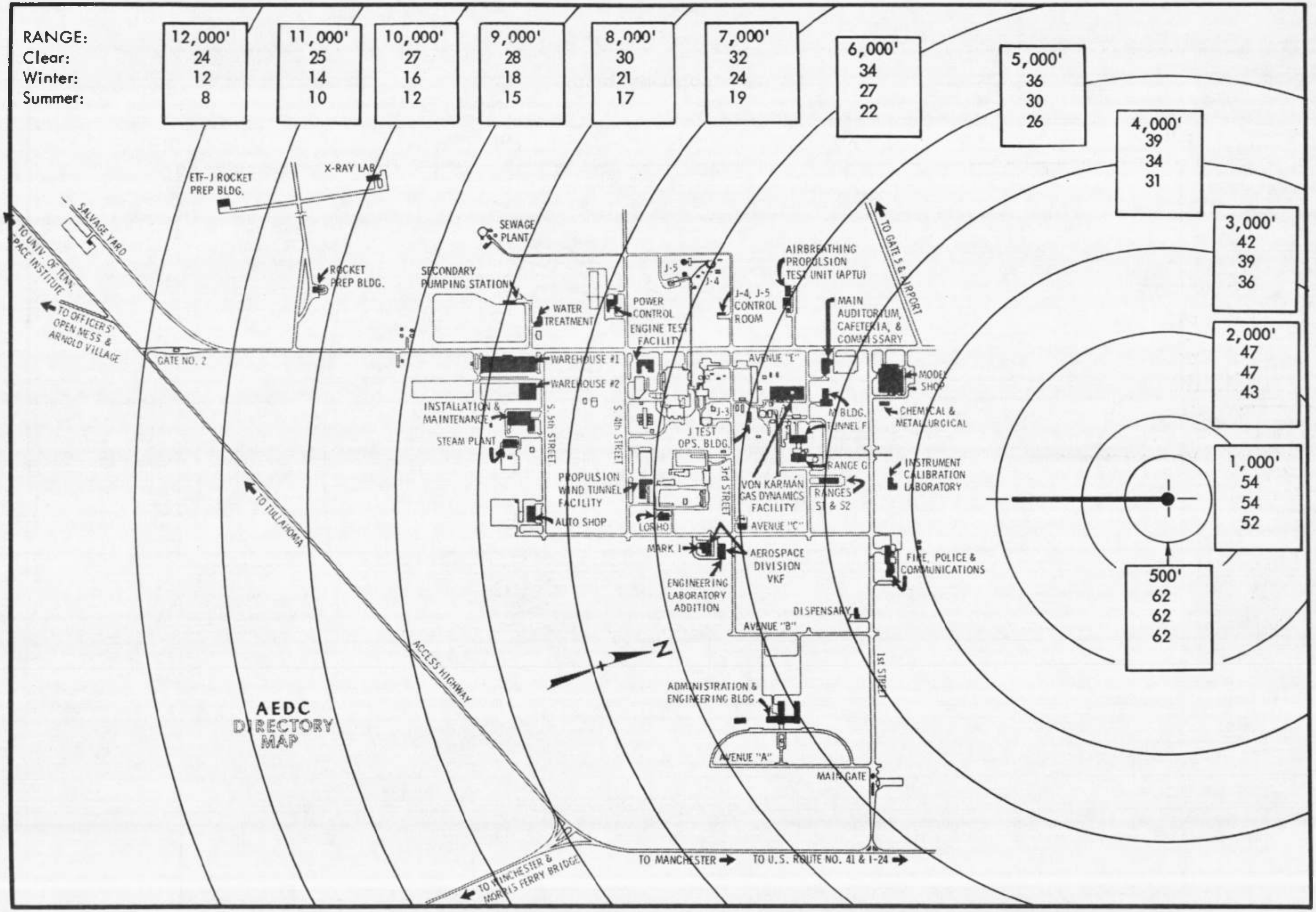


Figure 47. Contours of Constant Noise Exposure Forecast for AEDC Facilities

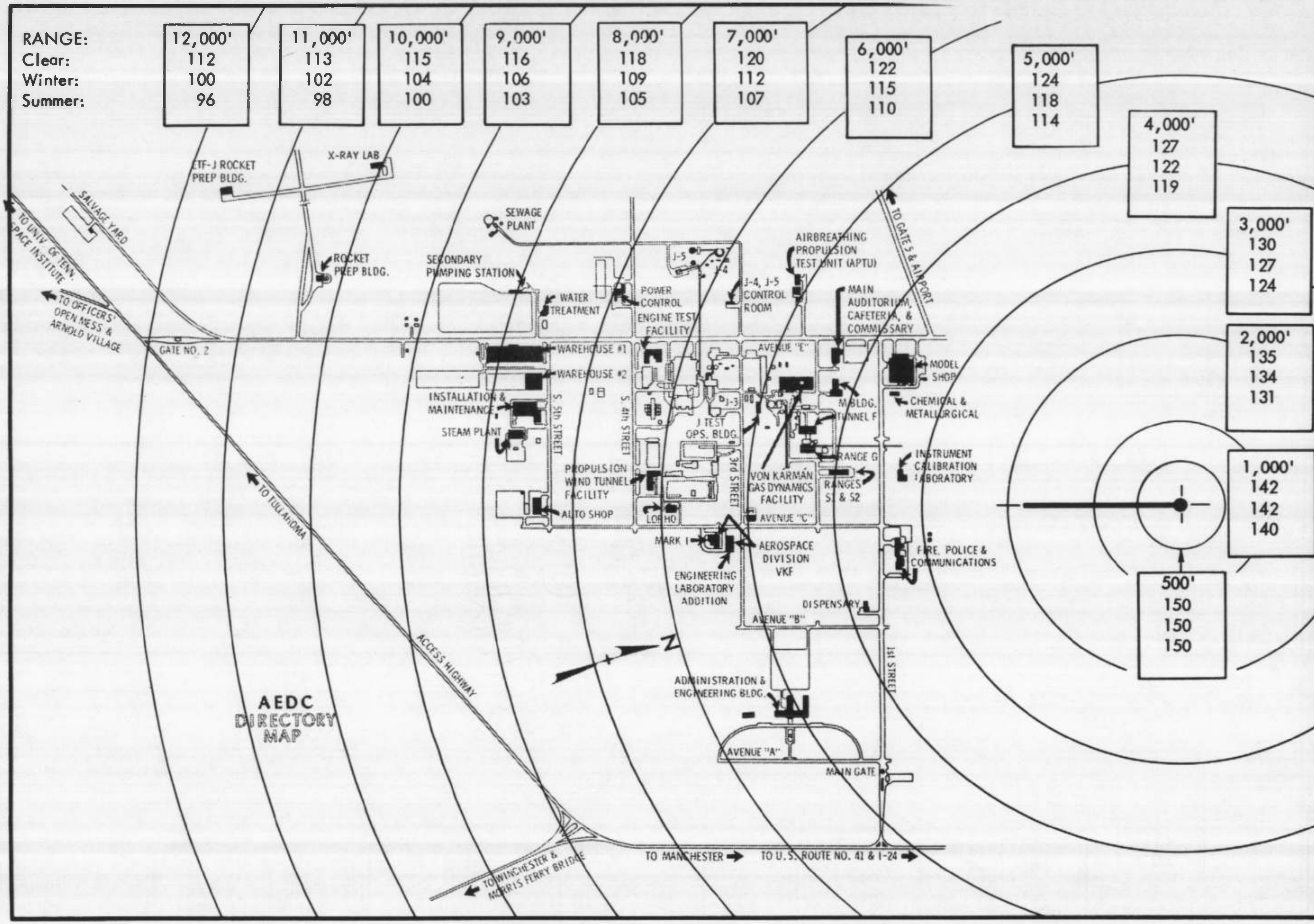


Figure 48. Contours of Constant Perceived Noise Levels for AEDC Facilities, Mass Flux of 165,000 lb_m/sec

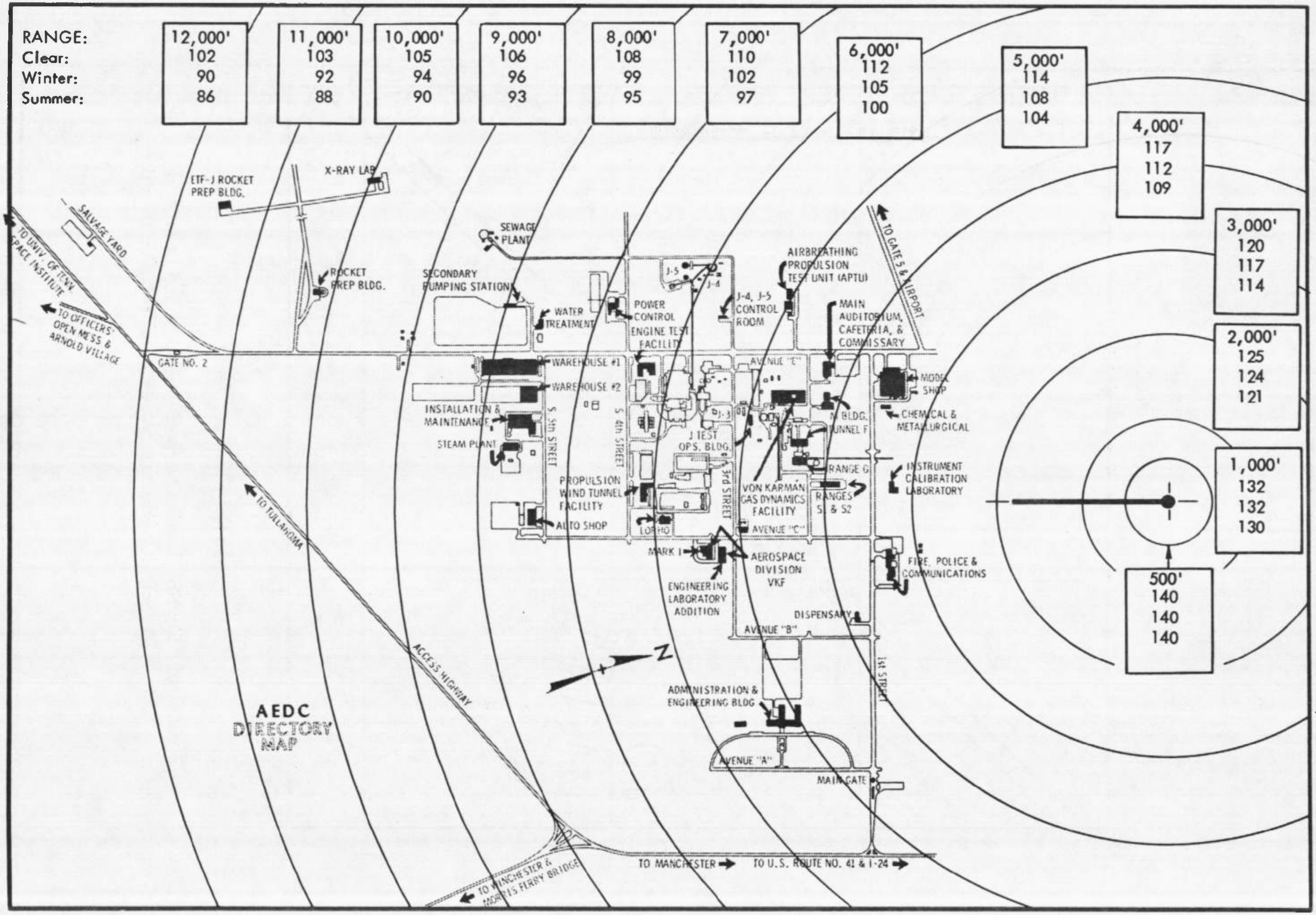


Figure 49. Contours of Constant Perceived Noise Levels for AEDC Facilities, Mass Flux of 165,000 lb_m/sec

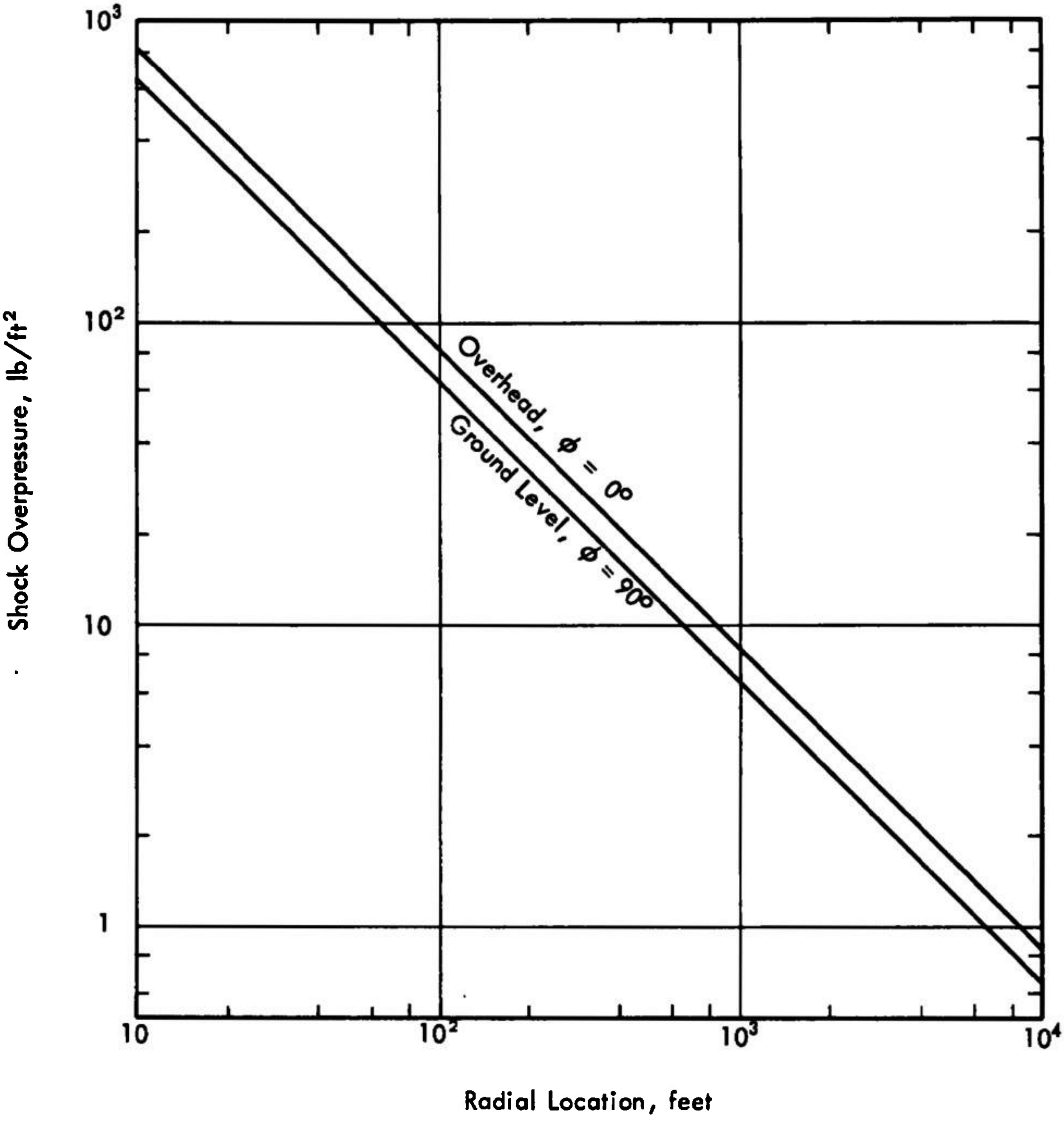


Figure 50. Starting Shock Overpressure at Ground Level and Directly Overhead, Mass Flux of 165,000 lb_m/sec

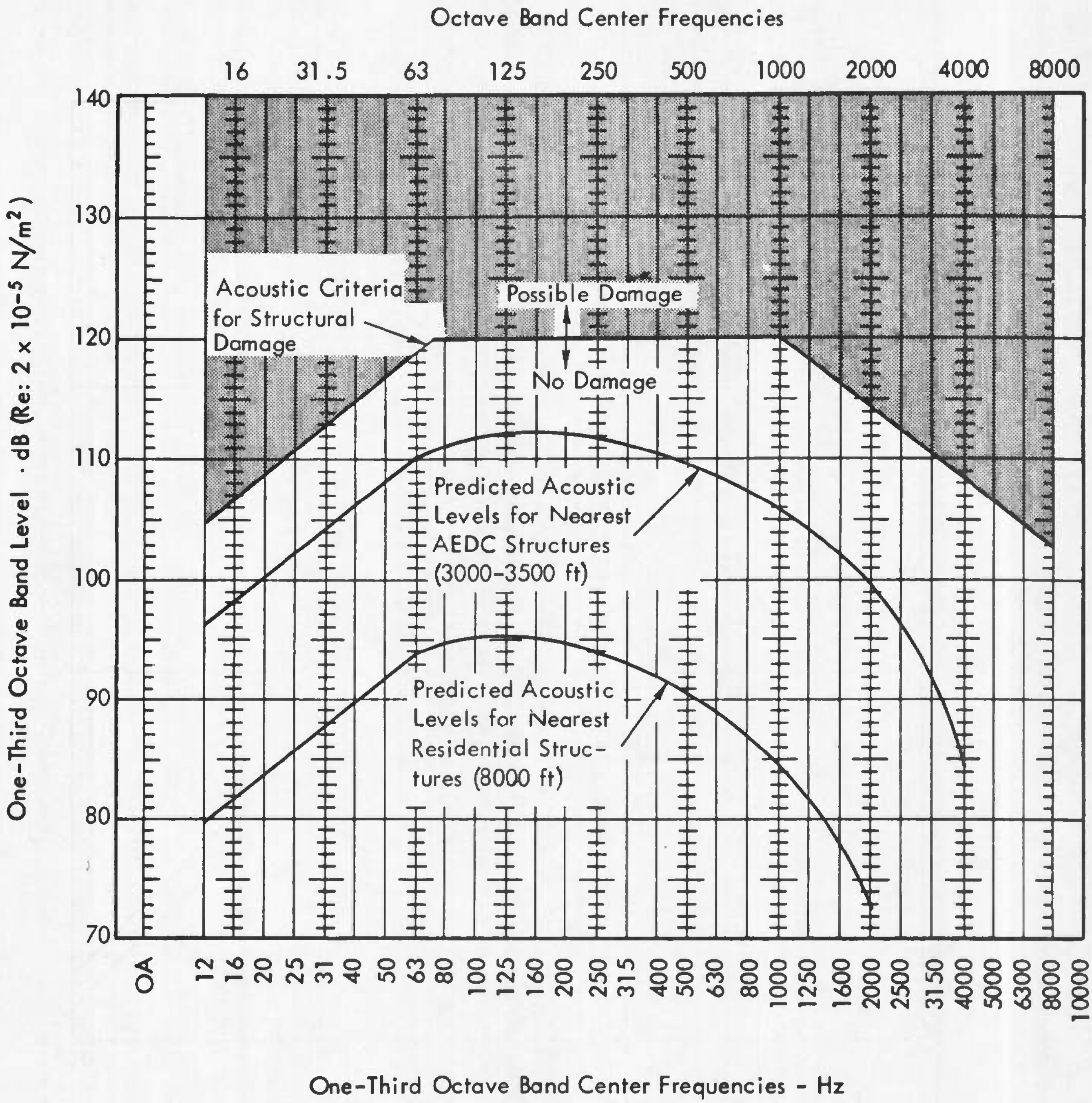


Figure 51. Comparison Between Expected Acoustic Levels for AEDC and Residential Structures and Acoustic Criteria for Structural Damage

Figure 52. View of the AEDC Model Shop Building; 3500 feet from HIRT Facility

APPENDIX A

THEORETICAL ANALYSIS OF THE STARTING SHOCK NOISE ENVIRONMENT

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1.0 STARTING PROCESS AND SONIC BOOM MODEL

The HIRT starting process is that of a constant mass flux source turned on in a time of 50 msec or less. This starting time is short compared to the total running time of approximately three seconds. Two approaches have been used to estimate the acoustic environment associated with the starting shock environment. First, the shock was treated as a blast wave by representing the energy of the starting shock with equivalent explosive charges. The propagational characteristics of the starting shock through the atmosphere was determined from equivalent blast wave propagation data. The predictions using this approach are reported in Reference A-1. The primary uncertainty associated with the blast wave model is in the decay characteristics of the shock wave. For a blast wave, the decay is intimately connected with the expansion immediately following the shock wave. This expansion reflects rapid cooling after the initial energy release of the explosion and represents a characteristic which will not be present in the HIRT starting shock environment. Because of the uncertainty associated with the blast wave model, a second approach has been employed in predicting the starting shock environment. This approach, described herein, is essentially a sonic boom model of the starting process.

Several hundred feet from the exhaust stack the Mach number of the exhaust gas is small. The starting wave pattern can be calculated by applying Lighthill's theory of sound generated aerodynamically (Reference A-2). The far-field signature, uniformly valid to first order, may then be found by applying Whitham's rule (Reference A-3) to the acoustic signature. The procedure is the same as in the calculation of sonic booms.

The wave pattern around the exhaust valves is extremely complicated. Because calculation of the actual flow is not practical, the valve arrangement will be modeled as sources distributed uniformly on a sphere whose area equals the total valve throat area. Although a more correct model would be cylindrically distributed sources, it is assumed that the spatial distribution of sources is small compared to the wavelength of the starting wave, so that in the far field the actual source distribution is not important.

The acoustic signal generated by a spherical source of radius r_0 is:

$$p - p_1 = \frac{\ddot{m}\left(t - \frac{r - r_0}{a_1}\right)}{4\pi r} \tag{A-1}$$

where the argument of $\ddot{m}$ indicates the acoustic signal is generated at r_0. The effect of stack geometry on directivity will be included later.

It should be noted that Equation (1) is correct only when source density equals ambient density, the signal being generated by the volume flux. For certain HIRT running conditions, density of the fully expanded exhaust may be several times the ambient value. The present calculation is therefore conservative, and may overestimate the starting shock.

At large distances from the source, the effect of finite wave amplitude on propagation speed must be taken into account. The change to Equation (1) is that $\ddot{m}\left(t - \frac{r-r_0}{a_1}\right)$ is replaced by $\ddot{m}\ (\tau)$, $\tau = t - \frac{r-r_0}{a_1} + \Delta t$, where

$$\Delta t = \frac{\gamma_1 + 1}{2\gamma_1 a_1} \frac{\ddot{m}\ (\tau)}{4\pi p_1} \log \frac{r}{r_0} \qquad \text{(A-2)}$$

for a spherical source. The signature is given by Equation (1) as "steepened" according to Equation (2). The steepening process is illustrated in Figure A-1. Where this construction results in the wave "folding over", a vertical line representing a shock wave is inserted such that the area of the pulse (without geometric attenuation) is conserved. In the far field, most signatures tend toward a triangular pulse, and the shock overpressure decays as $r^{-1}\ (\log r)^{-1/2}$. Signatures which have not yet reached the triangular shape are generally referred to as mid-field and decay of the shock depends on the signature shape.

The precise shape of $\ddot{m}$ depends on the operating characteristics of the valves. For purposes of these calculations, it will be assumed that $\dot{m}$ increases linearly during an opening time of 50 msec so that $\ddot{m} = \dot{m}/0.05$ sec. For these conditions, the acoustic wave will be a square pulse of 50 msec duration and overpressure given by

$$\frac{P - P_1}{P_1} = \left(\frac{\dot{m}}{0.05}\right)\left(\frac{1}{4\pi r}\right)\left(\frac{1}{P_1}\right) = \frac{\dot{m}}{0.2\pi r P_1} \qquad \text{(A-3a)}$$

The most extreme operating condition for HIRT is $\dot{m} = 165{,}000$ lb m/sec. For this condition the overpressure is given by

$$\frac{P - P_1}{P_1} = \frac{3.86\ \mathrm{ft}}{r} \qquad \text{(A-3b)}$$

The variation of absolute overpressure with radial location is shown in Figure A-2. Because this signal is a single pulse, it is not expected to be attenuated by passage over ground cover, since ground cover attenuation is based on destructive interference of different phases of a continuous wave.

The advance time Δt for a wave with overpressure given by Equation (3b) is

$$\Delta t = 2.91 \times 10^{-3}\ \mathrm{sec}\ \log \frac{r}{r_0} \qquad \text{(A-4)}$$

The wave is generated in the nozzle throats, total area 87 ft^2. The radius of a sphere with this area is 2.64 ft; this is the appropriate value to use for r_0. Figure A-3 shows Δt, with the shape of the pulse indicated at several points. Conserving area, it is clear that the total length of the pulse is 50 msec + 1/2 Δt; this is indicated. A triangular signature does not form until distances much larger than those of interest.

Also shown in Figure A-2 is the overpressure for zero starting time. It should be noted that lengthening the starting time would reduce the overpressure. For example, if the valve opening is 100 msec, $p - p_1$ would be half that given by Equations (3a) and (3b). Use of this may extend the environmentally acceptable operating conditions for HIRT; however, it will reduce the usable run time of the facility.

The total impulse of the starting wave can be an important factor in determining damage. The impulse per unit area is given by the time integral of pressure, over the pulse:

$$I = \int \left(p - p_1\right)\, dt \qquad \text{(A-5)}$$

Since momentum is conserved, the value of I obtained from the acoustic signature applies to the steepered signatures actually encountered. Thus, from Equation (1),

$$I = \int \frac{\ddot{m}\left(t - \frac{r - r_0}{a_1}\right)}{4\pi r}\, dt = \frac{\dot{m}}{4\pi r} \qquad \text{(A-6a)}$$

so that I depends only on $\dot{m}$, and does not vary with value opening time. For the present case,

$$I = 407 \frac{\text{lb - sec}}{\text{ft}^2} \frac{\text{ft}}{r} \tag{A-6b}$$

This is shown in Figure A-4.

2.0 WAVE SPREADING WITHIN EXHAUST STACK

A schematic representation of a spherical wave spreading within the exhaust stack is shown in Figure A-5. The primary wave, diffracted wave around the exit, and first reflected wave from the stack walls are shown; waves reflected from the lower hemisphere are not shown. The wave pattern at the exit shows the following characteristics:

- Distortion in the wave pattern due to the slight off-center location of the source (representative of the geometric center of the valve system).
- Diffracted wave pattern at the stack exit.
- Possible amplification to the primary wave by the reflected wave.

The distortion due to the source being off-center is slight. Since the actual source is distributed over an area large relative to its displacement from the center, it is reasonable to assume the source is centered. This simplifies the geometry considerably. Figure A-6 shows the stack with the source centered, and several acoustic rays (normal trajectories to wavefronts). For the dimension shown in the figure, rays between $0 \leq \phi \leq 30^\circ$ emerge from the stack without contacting the walls. This segment thus represents the primary waves. Rays between $30^\circ \leq \phi \leq 60^\circ$ experience one reflection. Rays between $60^\circ \leq \phi \leq 67^\circ$ are reflected twice. It is easy to see that a reflected ray emerging at an angle $\phi \leq 30^\circ$ has a path at least 80 feet longer than a primary ray (counting the actual size of the source from reflections from the bottom). This is longer than the length of the signal calculated in the previous section, so reflected waves do not interact with the primary wave. The primary wave may be calculated on the basis of the spherical segment $\phi \leq 30^\circ$. Secondary waves may follow, but will be attenuated dur to reflection losses. Rays emerging at $\phi > 30^\circ$ will have had at least one wall reflection and one focus per reflection. There is additional attenuation in passing through a focus due to nonlinear distortion, although all mechanisms at a focus are not yet fully understood.

On the basis of the above discussion, it is concluded that secondary waves will follow the primary wave, and their amplitude will be small (or, at worst, no larger than) compared to the primary wave and the diffracted wave estimated in the next section.

3.0 DIFFRACTION AT STACK EXIT — FAR-FIELD OVERPRESSURE CONTOURS

The spherical wave exiting from the exhaust stack may be likened to a spherical piston at the end of a tube. Reference A-5 provides far-field angular distribution of acoustic overpressure for harmonic oscillation of a flat piston at the end of a tube. This depends on the factor $\omega r/a_1$, where r = radius of tube and $\omega = 2a_1/\lambda$, λ = wavelength. The impulse of the starting signal may be characterized by a harmonic wave with λ twice the signal duration. For $r = 43$ feet and a 50 msec pulse, $\omega r/a_1 = 2.4$. The angular attenuation, based on Reference A-4, is 4 dB/30° . Since the present case is a spherical piston of half angle 30°, the distribution will be uniform for $\phi \leq 30°$, with the 4 dB/30° fall-off applying to $\phi \geq 30°$. Figure A-7 gives the overpressures as functions of ϕ for several distances. The values for $\phi \leq 30°$ correspond to Figure A-2.

The angular distribution in Figure A-7 does not include pressure doubling at $\phi = 90°$ due to ground reflection. This was omitted because, under certain meterological condition, rays representing $\phi < 90°$ may be refracted down to the ground. The appropriate ground reflection factor is, therefore, to be applied to each case.

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A-1 Robertson, J.E., and Pao, S.P., "Noise Environment of the Proposed AEDC High Reynolds Number Tunnel — Theoretical Prediction and Model Test Plan," Wyle Laboratories Research Staff Report WR 69-20, September 1969.

A-2 Lighthill, M.J., "Sound Generated Aerodynamically," Proceedings of the Royal Society, A, Vol. 267, pp. 147-182 (1962).

A-3 Whittam, G.B., "On the Propagation of Weak Shock Waves," Journal of Fluid Mechanics, Vol. 1, No. 3, pp. 209-318 (1956).

A-4 Robertson, J.E., "Model Study of the Exhaust Flow Noise of the Proposed AEDC High Reynolds Number Tunnel," AEDC-TR-71-146, July 1971.

A-5 Beranek, Acoustics, McGraw-Hill, New York, 1954.

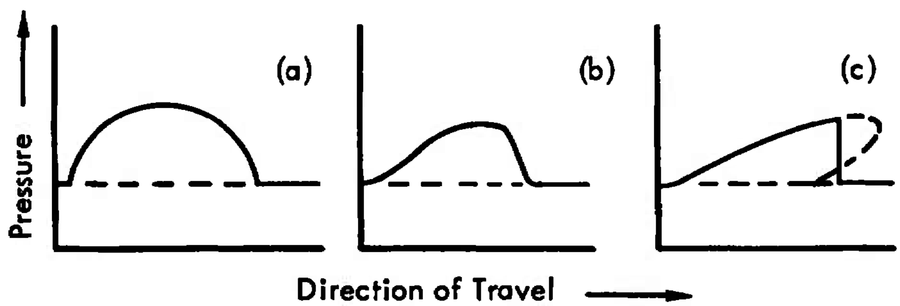

Figure A-1. Illustrating the Development of Explosive Shock. Assumed initial pressure pulse is shown as (a) and successive configurations (b) and (c) are formed by differing speeds of its parts.

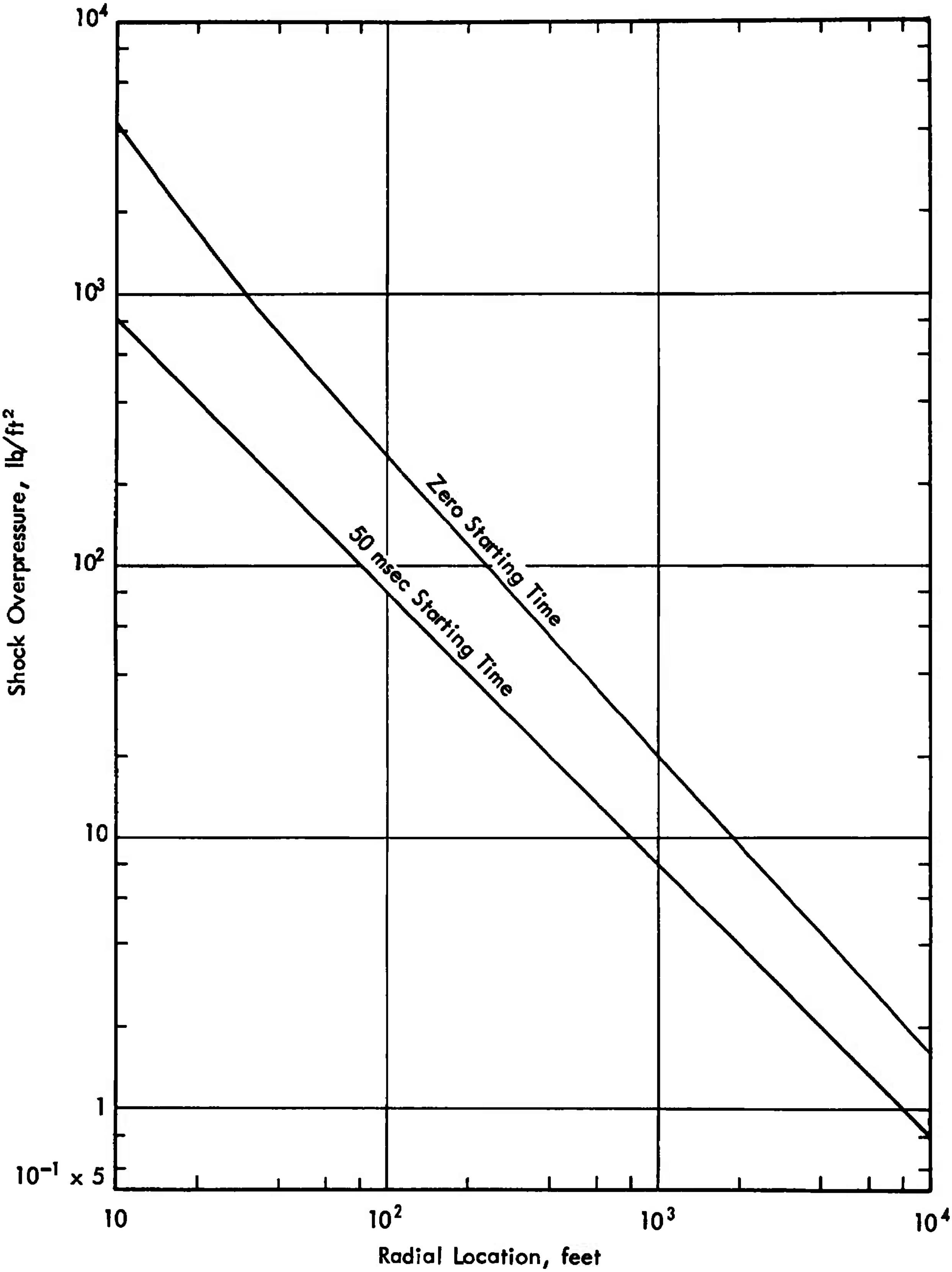

Figure A-2. Variation of Starting Shock Overpressure with Radial Location, $\dot{m}$ = 165,000 lb/sec

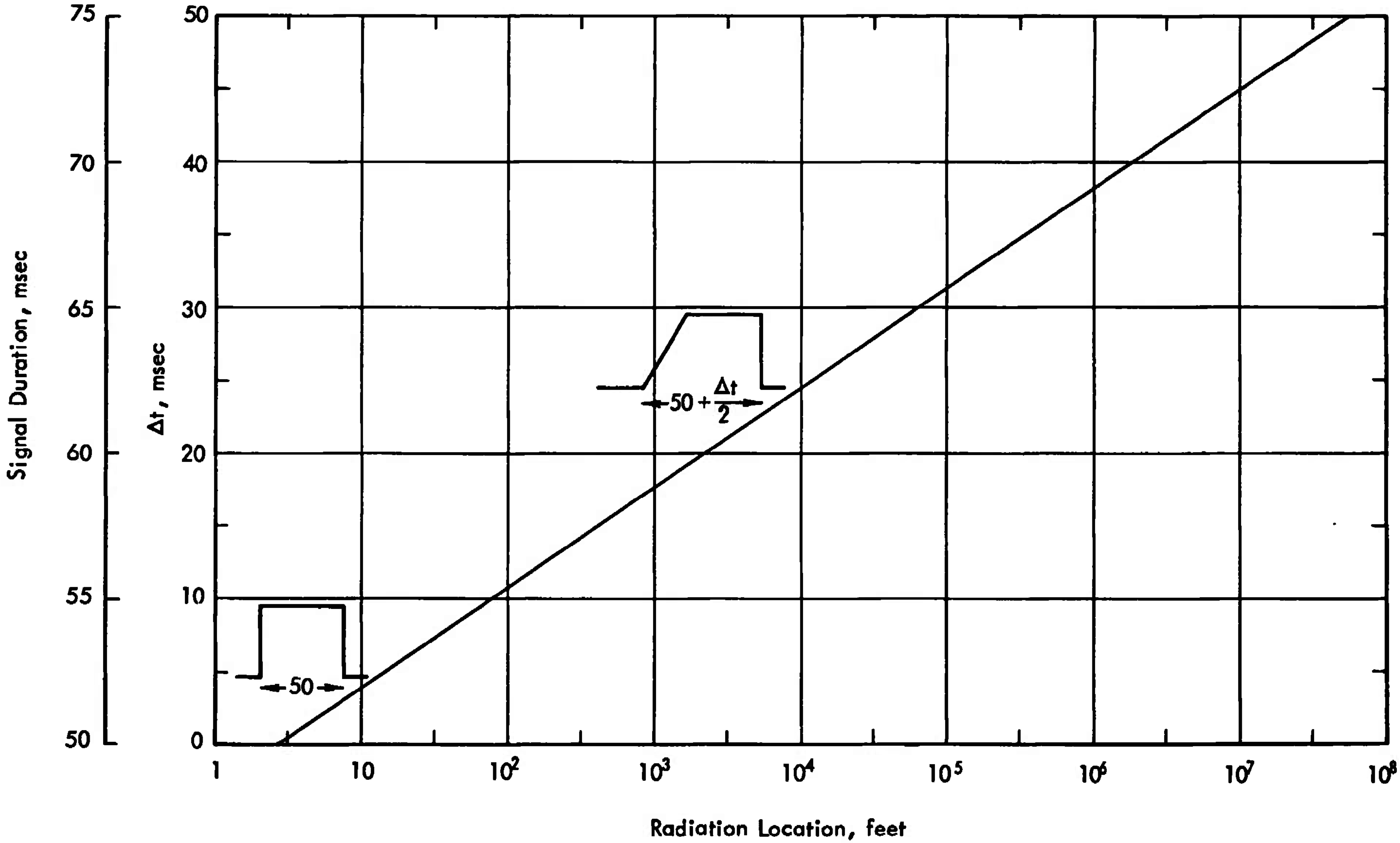

Figure A-3. Advance Time and Pulse Length for Starting Wave

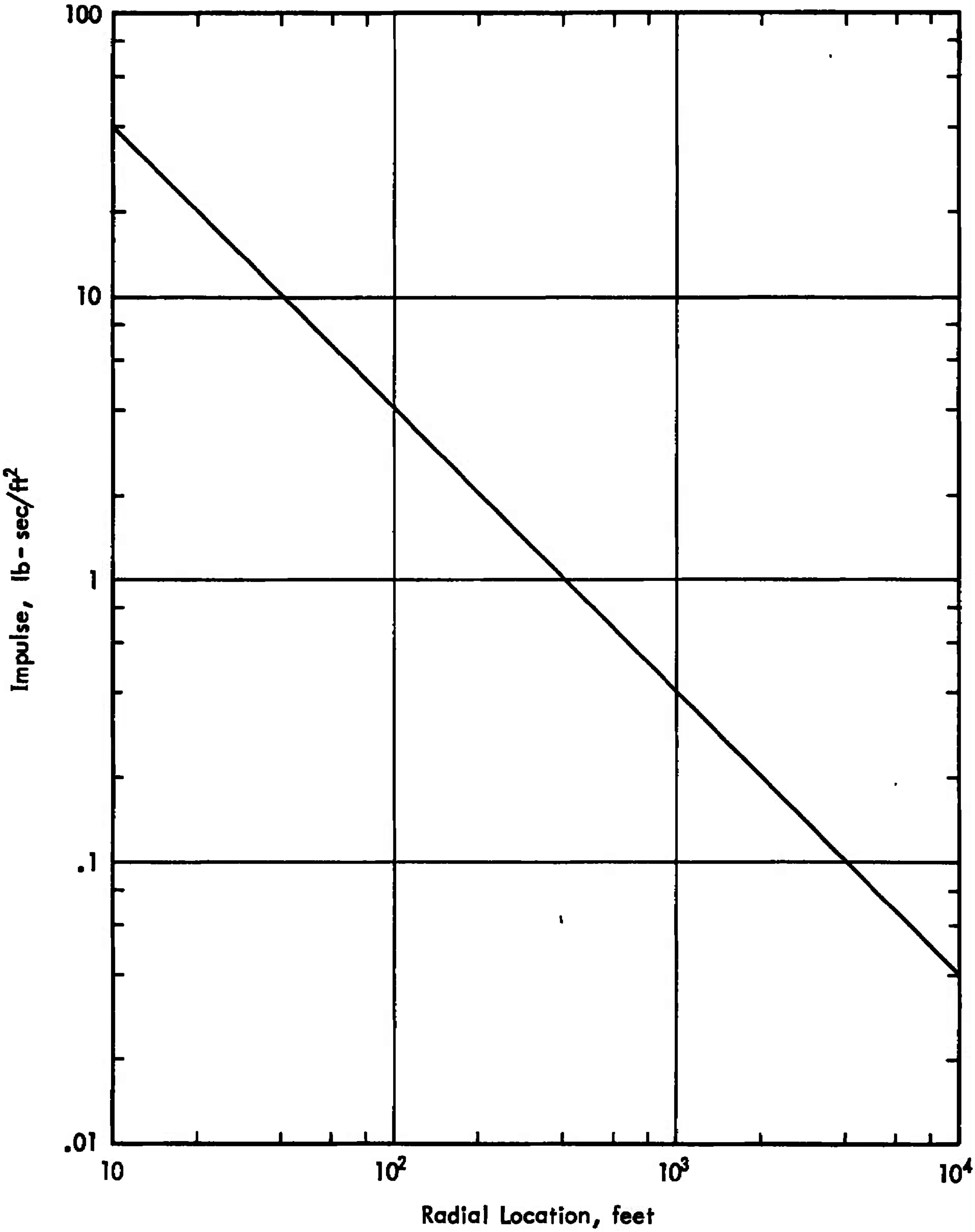

Figure A-4. Variation of Starting Shock Impulse with Radial Location, $\dot{m}$ = 165,000 lb/sec

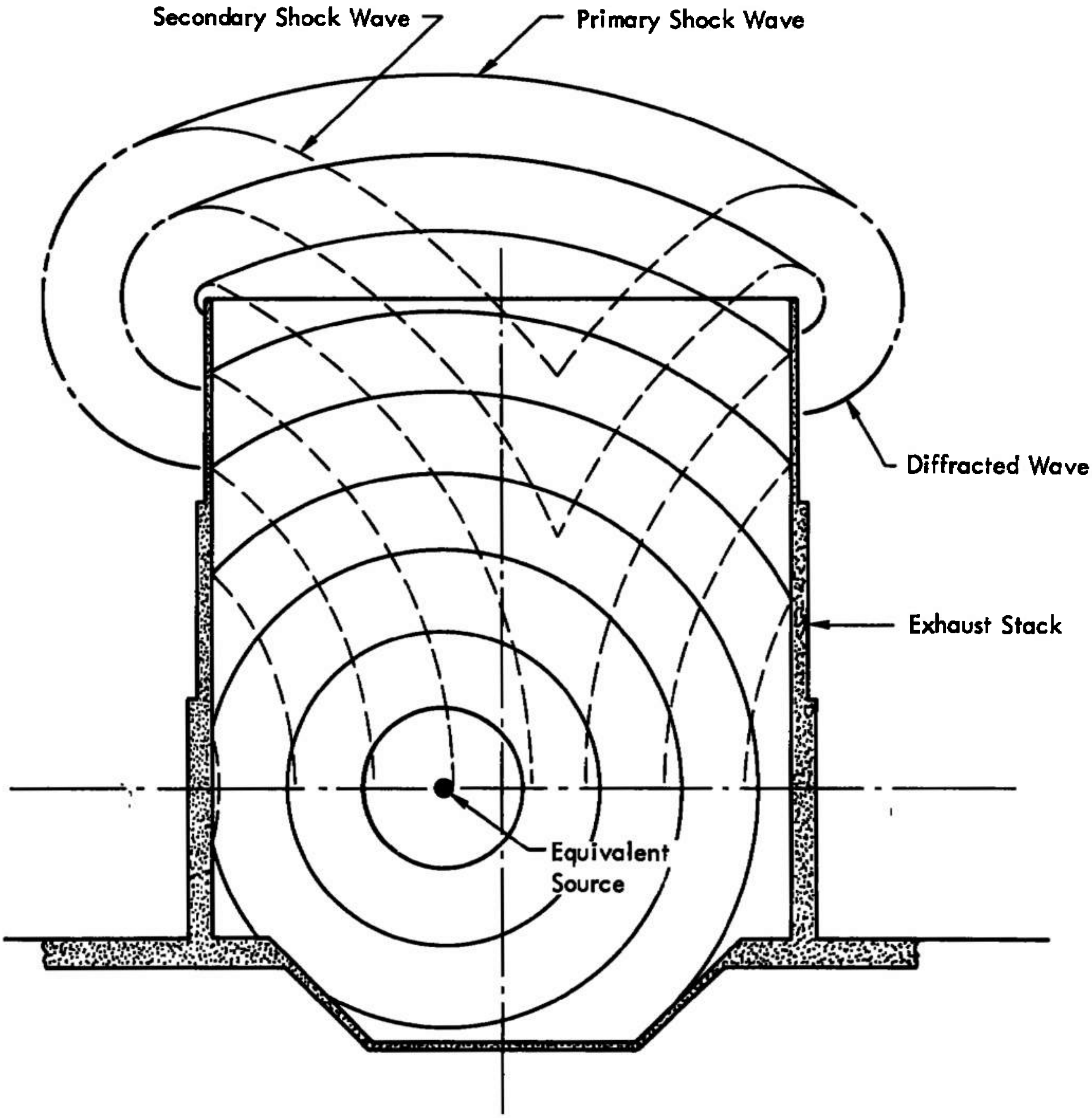

Figure A-5. Starting Shock Wave Propagation for the Exhaust Stack Using an Energy Equivalent Source

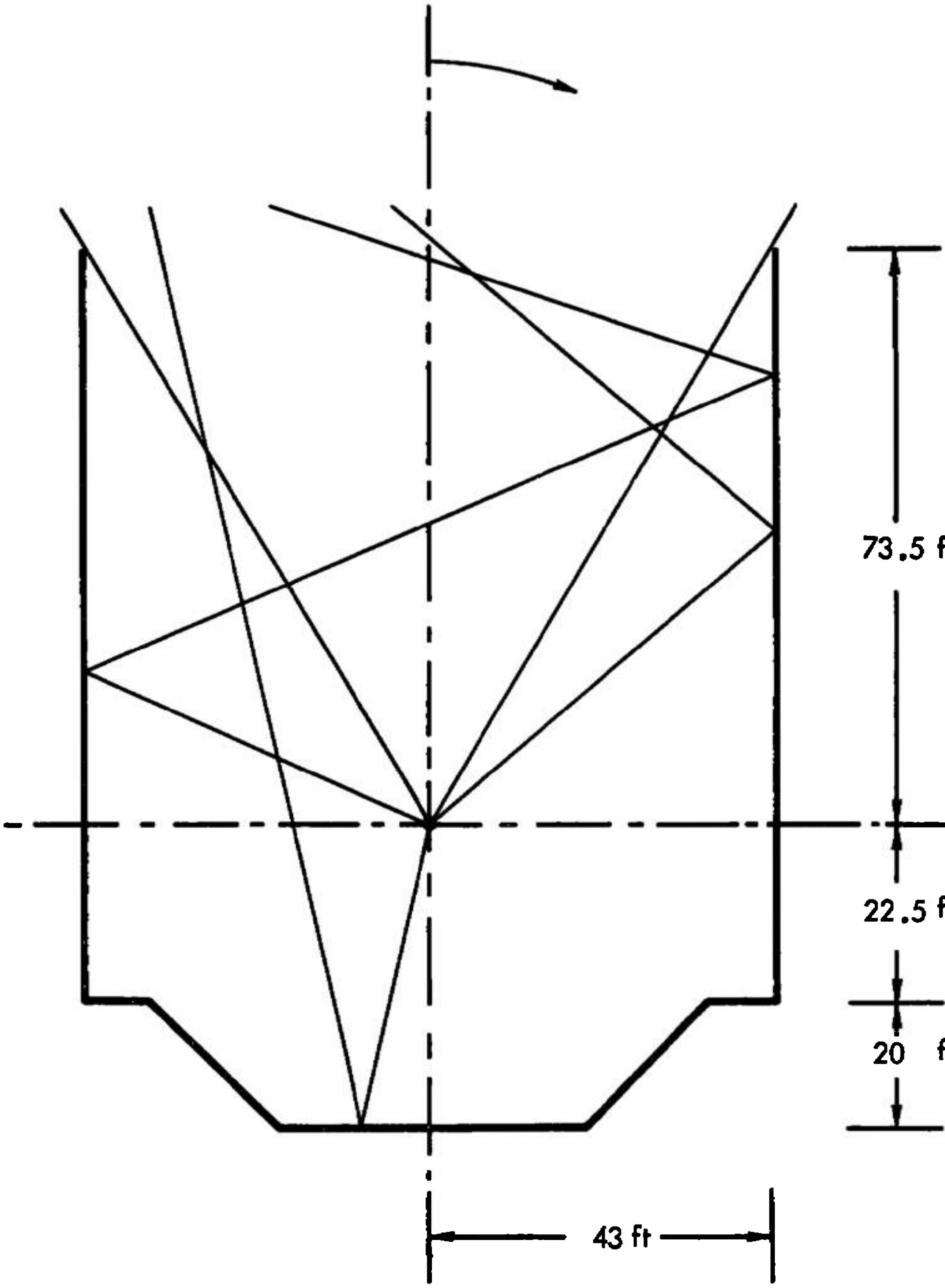

Figure A-6. Acoustic Rays Within Stack

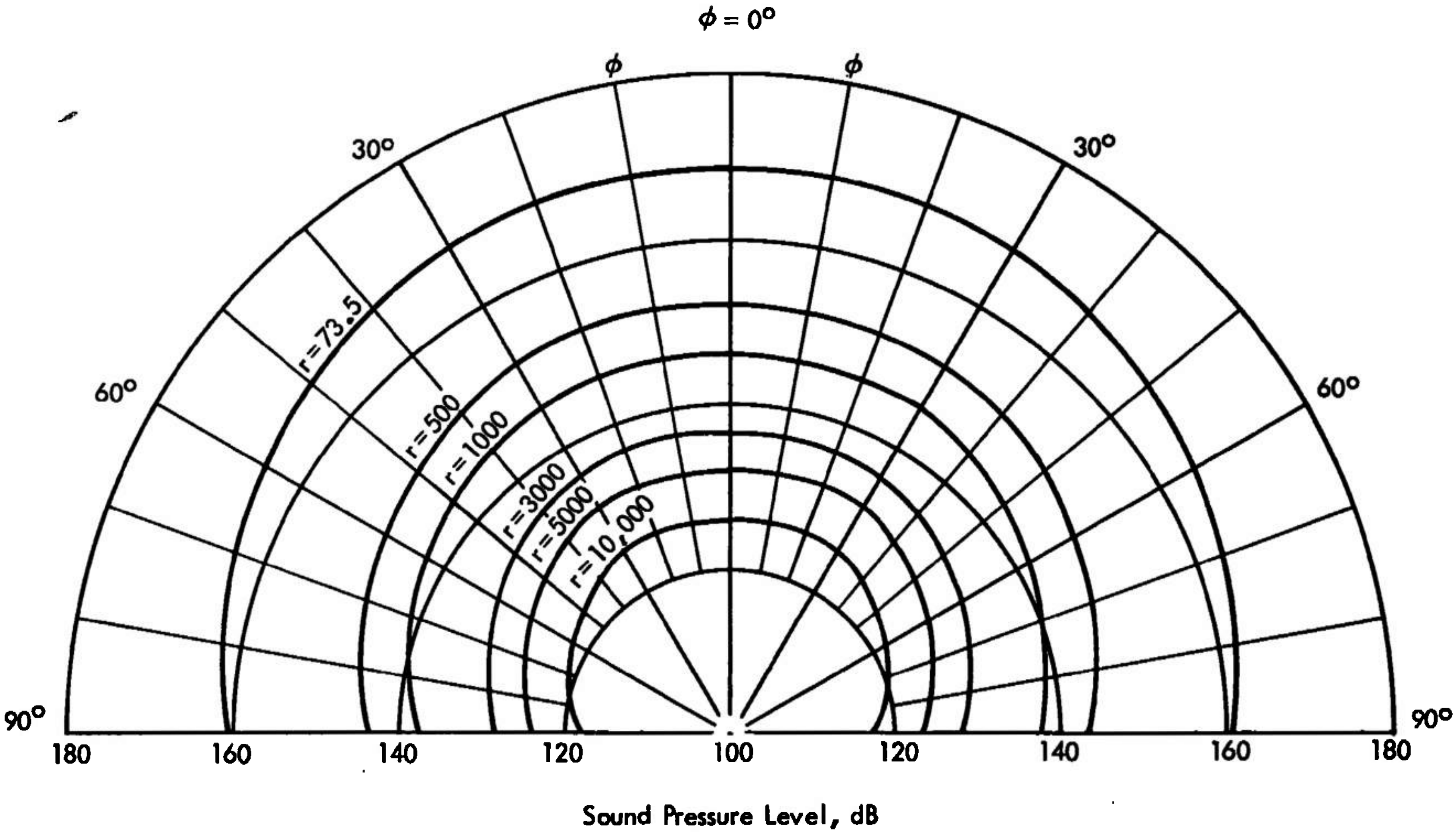

Figure A-7. Far-Field Sound Pressure Levels for the Starting Shock Wave of HIRT

APPENDIX B

ANALYSIS OF NOISE PROPAGATION LOSSES DUE TO GROUND ATTENUATION AND AIR ABSORPTION

APPENDIX B

ANALYSIS OF NOISE PROPAGATION LOSSES DUE TO GROUND ATTENUATION AND AIR ABSORPTION

1.0 INTRODUCTION

A basic characteristic of sound propagation is the attenuation with distance due to various irreversible processes which remove energy from an acoustic wave and convert it to heat. Where it is necessary to evaluate sound propagation over a substantial number of wavelengths, as in the case of HIRT, the propagation characteristics are dependent upon:

- atmospheric conditions
- the positions of the source and receiver relative to the ground
- the terrain/vegetation features adjacent to the sound path.

These conditions can be classified as follows:

- Absorption by ground and ground cover
- Absorption by the atmosphere.

Analyses of the noise propagation losses due to these effects have been performed in support of this program. A cursory analysis of these losses were included in Reference B-1. However, in view of the importance of these parameters and the availability of recent publications on the subject (see References B-2 through B-6), the effects of natural ground cover and the molecular absorption of sound in air have been examined in considerable detail in order to arrive at new and more accurate estimates of the HIRT noise environment. A discussion of these analyses are presented in this appendix.

2.0 GROUND ATTENUATION

2.1 <u>Computation Method</u>

As sound propagates over a vegetated terrain, there are three basic paths which the wave can take:

- a straight line between the source and receiver
- reflect off the top of the vegetation and then procede to the receiver
- pass through the vegetation and reflect off the ground and then pass back through the vegetation and then procede to the receiver.

It is the interaction between these three waves that causes an excess attenuation greater than that which would be expected for no terrain effects.

The prediction of ground attenuation is far from being a simple, straightforward problem due to the complex acoustic properties of natural vegetation and the physics associated with the interaction of sound with the ground cover. For natural ground covers, the boundary between the upper and lower acoustic media (the air and the ground) is not a simple plane as assumed by most theories, but a porous layer with finite thickness. For ground covers such as forested areas consisting of trees and undergrowth, it is necessary to treat the ground cover as a composite boundary of porous acoustic material in order to arrive at realistic estimates of ground attenuation. This requirement becomes even more stringent for sound propagation at near glancing angles of incidence typical of HIRT noise propagation over surrounding land areas. A recent mathematical model, based on a layered media representation of natural ground covers, has been developed by Wyle Laboratories (References B-2 and B-3). This theory has been previously checked through laboratory-scaled experiments with good agreement with experimental observables. In Reference B-3, the theory was applied to the prediction of sound attenuation over various types of ground covers composed of natural vegetation. The results of this study form the basis for the present analysis of ground attenuation effects on HIRT noise propagation.

The mathematical details of the prediction scheme for computing ground attenuation effects are considered to be beyond the scope of the present study and the reader is referred to Reference B-2 for a complete description of the theory. It suffices to note that a digital computer program has been prepared based on the theory presented in Reference B-2 and is given in Reference B-3. Given a mathematical definition of source height, receiver height, and the relevant mechanical and acoustical properties of the natural vegetation, the program computes the spectral sound attenuation at selected radial distances from the source. The problem is reduced to one of accurately selecting the mechanical and acoustical properties of ground cover to be representative of the vegetation under consideration.

The physical properties of the trees and undergrowth at AEDC have been specified in mathematical terms to facilitate the prediction of ground attenuation effects on the HIRT noise spectra. In Reference B-3, an extensive review of literature on agriculture and forestry was performed in order to arrive at representative physical properties for various types of vegetation. Based on these results, the salient properties which are required to define the acoustic effects of ground covers are specified by the following porous media characteristics.

- Ground Cover Layer Thickness, H
- Porosity, Y
- Effective Density, ρ_m

- Alternating Flow Resistance, R_1
- Specific Admittance Coefficient at the Ground, β_2
- Structure Factor (Nature of intersticies of vegetation skeleton), k
- Volume Coefficient of Elasticity of Acoustic Material, Q

In addition to specification of the above acoustic properties of the ground cover, the following geometric features of the noise field are required:

- Source height above vegetation canopy, H_s
- Receiver height above vegetation canopy, H_r
- Source-to-Receiver Propagation Distance, r

2.2 Characteristics of AEDC Vegetation and Terrain

The ground surface of the AEDC reservation and surrounding land areas is characterized by gently rolling terrain lying in the range of 950 to 1150 feet above sea level. The reservation includes 31,701 acres of forest land consisting of various species of oak, hickory, popular, maple, cedar, beech, gum and pine (see Section I). Representative aerial photographs of land areas at the center are shown in Figures B-1 to B-3. Most of the trees at AEDC are of the broad leaf, decideous variety, such that a significant change in ground attenuation may be anticipated with a seasonal change from summer to winter conditions.

For this reason, two seasonal conditions have been considered 1) summer season when vegetation is considered to be at maximum foliage and 2) winter season when vegetation is considered to be at minimum foliage. The acoustic properties of the AEDC ground cover for these seasons are specified as follows:

		Summer	Winter
H	=	40.000 feet	40.000 feet
Y	=	0.996	0.996
ρ_m	=	0.200	0.050
R_1	=	15.000	3.000
β_2	=	0.250	0.200

k	=	1.000	1.000
Q	=	1000.000	1000.000

These conditions are considered to be typical of land areas surrounding the proposed site of the HIRT facility. At the present time, heavy vegetation exists at the proposed site of HIRT, and maximum effort will be made to retain as much forested area as possible during the construction of the facility. Also, roads leading to the facility will be such that cleared right-of-ways pointing to the HIRT exhaust stack will be avoided wherever possible. Any right-of-ways, lakes, or other deviations from homogeneous vegetation may reduce the ground attenuation effect.

The following geometric features of the noise field have been employed in the ground attenuation computations.

H_s = 60 feet

H_r = 0 feet

r = variable from 500 to 64,000 feet

2.3 Prediction of Ground Attenuation Spectra

Ground attenuation spectra for typical summer and winter ground covers are presented in Figures B-4 and B-5, respectively. For each season a range of radial distances from the HIRT exhaust stack are given. Ground attenuation effects for relative thick ground covers such as trees show the largest attenuation at low frequencies. The attenuation decreases with increasing frequency. A comparison of the two figures reveal that the summer season results in attenuation levels significantly larger than corresponding levels for winter vegetation.

2.4 Effects of Ground Attenuation on HIRT Noise Spectra

The predicted effects of ground attenuation have been incorporated into the one-third octave band spectra as shown in Figures B-6 and B-7. For this comparison, inverse square spreading losses and atmospheric absorption effects have been omitted such that, variations in spectra shape result only from ground attenuation effects. At large distances and low frequencies, the ground attenuation approaches 6 dB reduction in spectrum level with doubling in distance. The most significant effect occurs at low frequencies. The net effect of low frequency attenuation on the spectrum shape is that the peak in spectrum level is shifted to higher frequencies with increasing distance from the source, combined with an overall reduction in spectrum level. Data presented in Figure B-6 represent ground attenuation effects for summer vegetation, whereas results presented in Figure B-7 represent ground attenuation effects for winter vegetation.

3.0 AIR ABSORPTION

3.1 Computation Method

The effect of molecular interactions on the absorption of sound in air have been studied extensively in the past few years culminating in the material contained in References B-4 through B-6. It has been shown that air can be treated as a four component gas, i.e., nitrogen, oxygen, carbon dioxide, and water vapor. The results of this analysis are contained in Reference B-4. The agreement between experiment and the analysis is very good. The analysis has been extended from the complicated computational method described in Reference B-4 to a set of easily programmed analytical expressions (Reference B-5) which have been used in the HIRT analysis. These analytical expressions agree within 3% of the tables in Reference B-6 which are based on the theory of Reference B-4 over a frequency range of 100 Hz to 1 MHz. Below 100 Hz the accuracy cannot be fairly judged in either the theory or the analytical expressions

3.2 Characteristics of AEDC Meteorological Conditions

A generally moderate year-round climate prevails in the middle Tennessee area; however, occasional extremes of cold and heat can be expected for very brief durations. During the past twelve years, the temperature extremes have been 106°F and minus 10°F with an average annual temperature of 57.3°F. Precipitation ranges from a dry year of 36 inches to a maximum of 67 inches. Average precipitation is 54 inches per year. Snowfall occurs from two to five times annually but rarely remains on the ground longer than one week and rarely exceeds 6 inches in depth. The frostline is considered to be 13 inches below existing grade and the average length of the frost-free growing season is 190 days.

For air absorption analysis purposes a temperature of 68°F was used for the HIRT predictions. This is approximately 10°F higher than the yearly average temperature. However, this difference will not significantly affect the predictions. At present, characteristics of the temperature dependence of air absorption are not well understood but for small deviations the effects will be small.

3.3 Prediction of Air Absorption Spectra

Air absorption spectra have been computed for a range of relative humidity values from 0% to 100% in Reference B-6. Humidity is the most significant parameter in the variation of absorption spectra; however, the effects are primarily confined to the lower range of humidity values, below 25% relative humidity. Typical air absorption spectra are presented in Figures B-8 and B-9. These data represent relative humidities of 50% and 100% at 68°F and the trends clearly show the increase in absorption with increasing frequency. For frequencies below 1000 Hz, the air absorption will generally be less than 1 dB/1000 ft.

3.4 Effects of Air Absorption on HIRT Noise Spectra

The predicted effects of air absorption have been incorporated into the one-third octave band spectra of the HIRT exhaust flow noise as shown in Figure B-10 for 50 percent relative humidity. For this comparison, inverse square law spreading losses and ground attenuation effects have been omitted such that, variations in spectra shape result only from air absorption. At high frequencies, the air absorption effect is clearly evident in the high roll-off of the spectrum levels. The roll-off increases with both increasing distance and increasing frequency with a corresponding movement of the spectrum peak level to lower frequencies. Since the effects of air absorption are appreciable in the most sensitive audible range (3000 Hz), the absorption losses will be very effective in reducing the subjective annoyance of HIRT noise in the far field.

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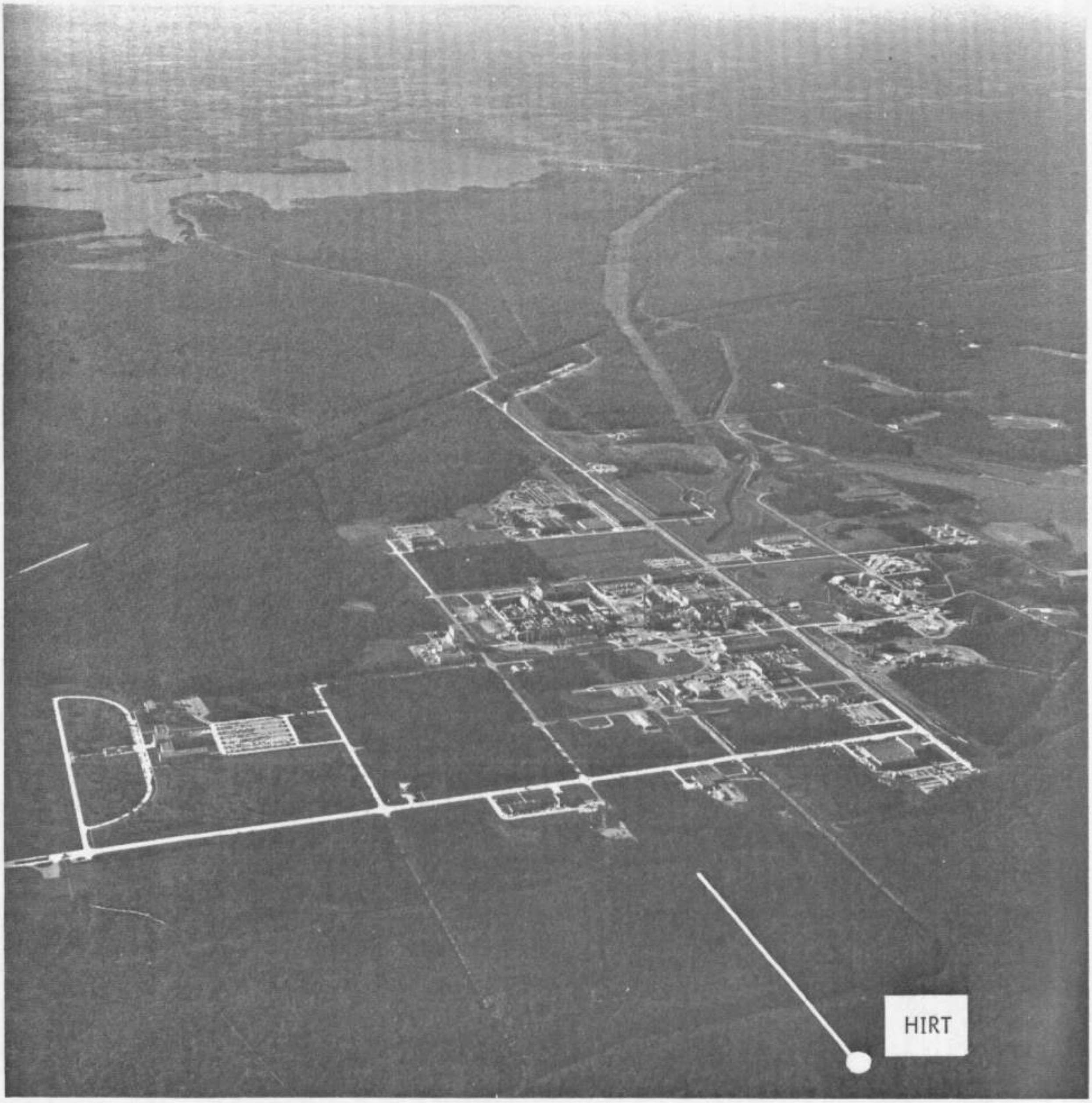

Figure B-1. Aerial View of AEDC Looking Southwest

Figure B-2. Aerial View of Future HIRT Site Looking Northeast
(Instrumentation Calibration Lab shown in Foreground)

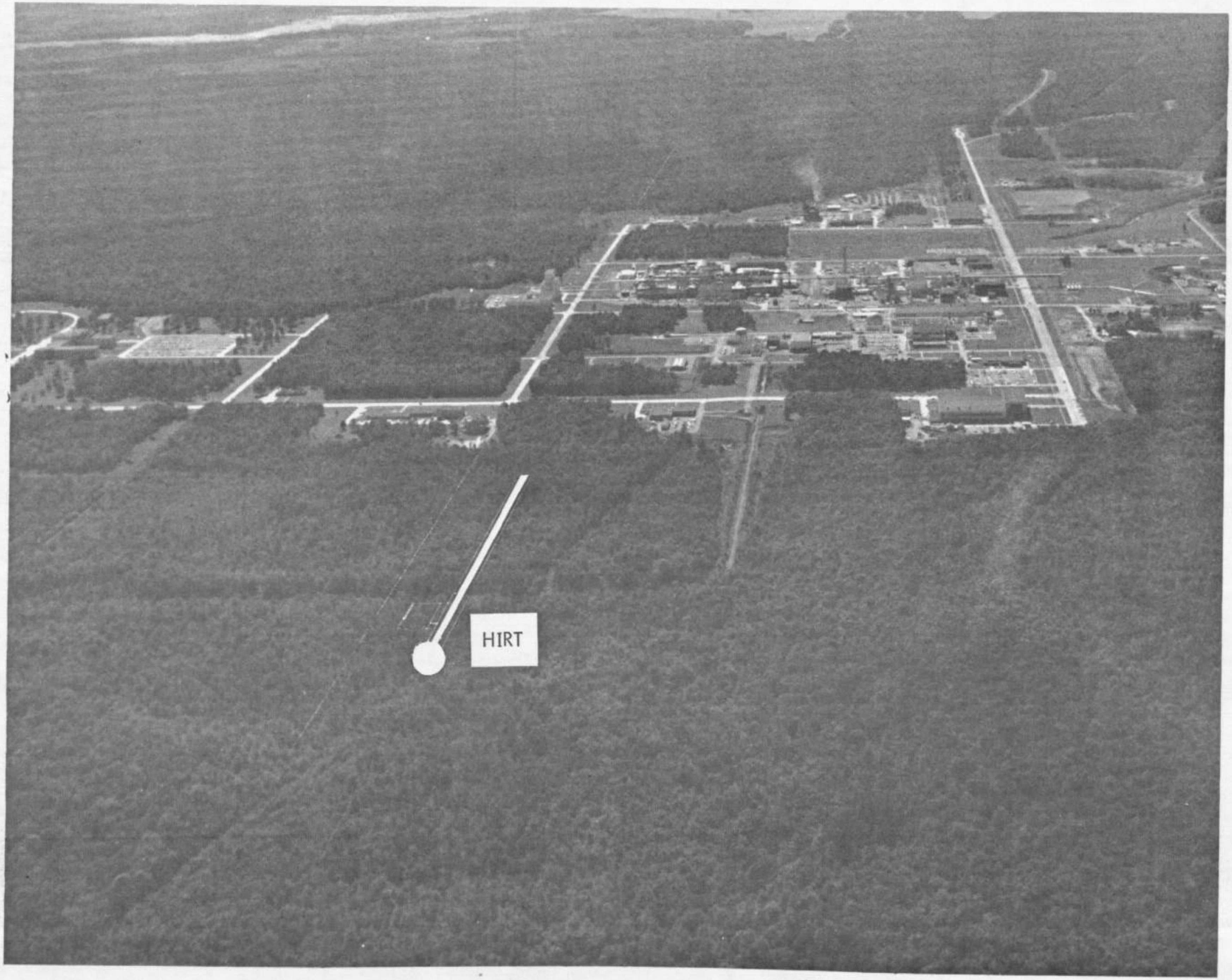

Figure B-3. Aerial View of Future HIRT Site Looking South

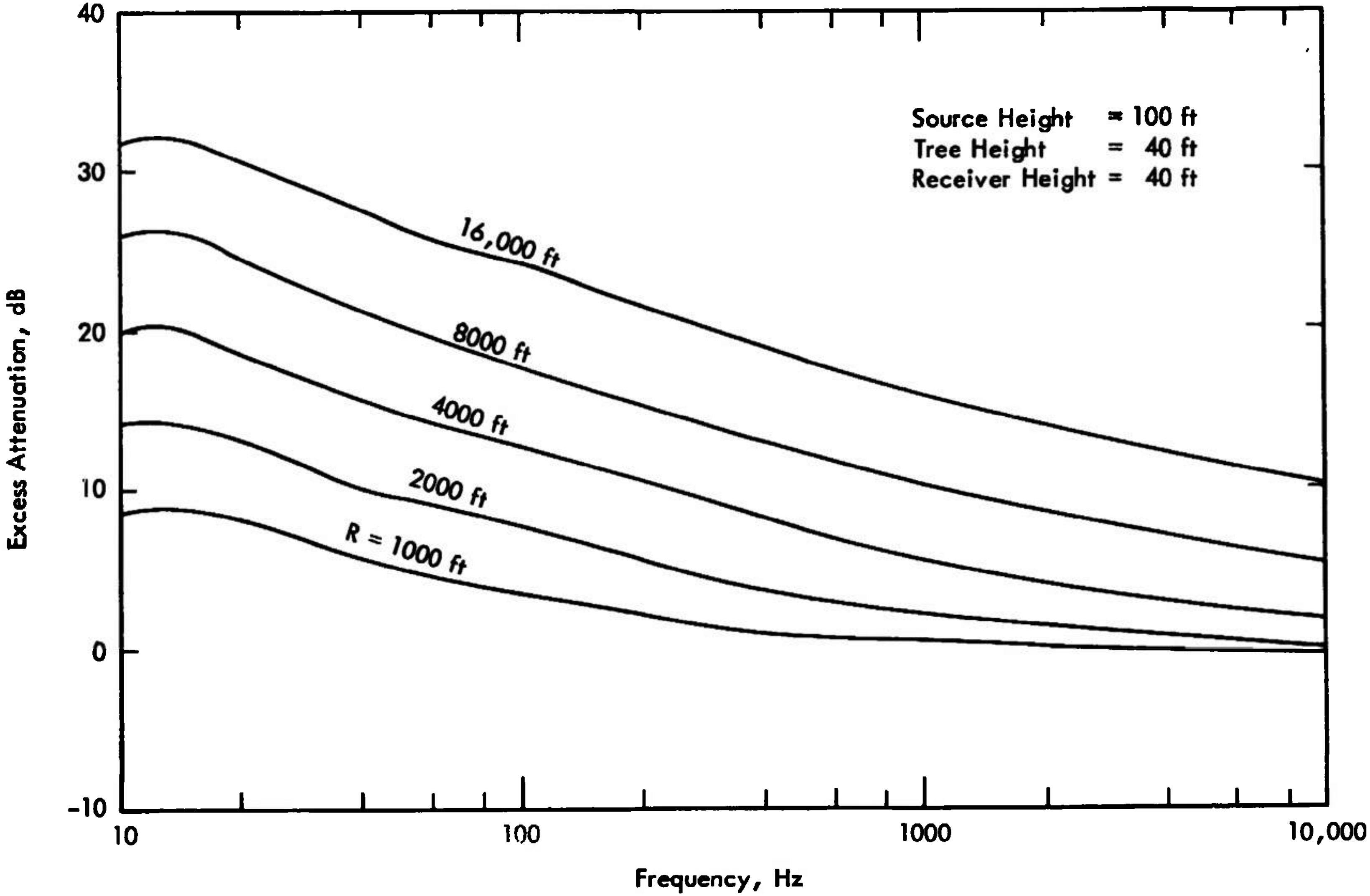

Figure B-4. Excess Attenuation Spectra for Summer Ground Cover

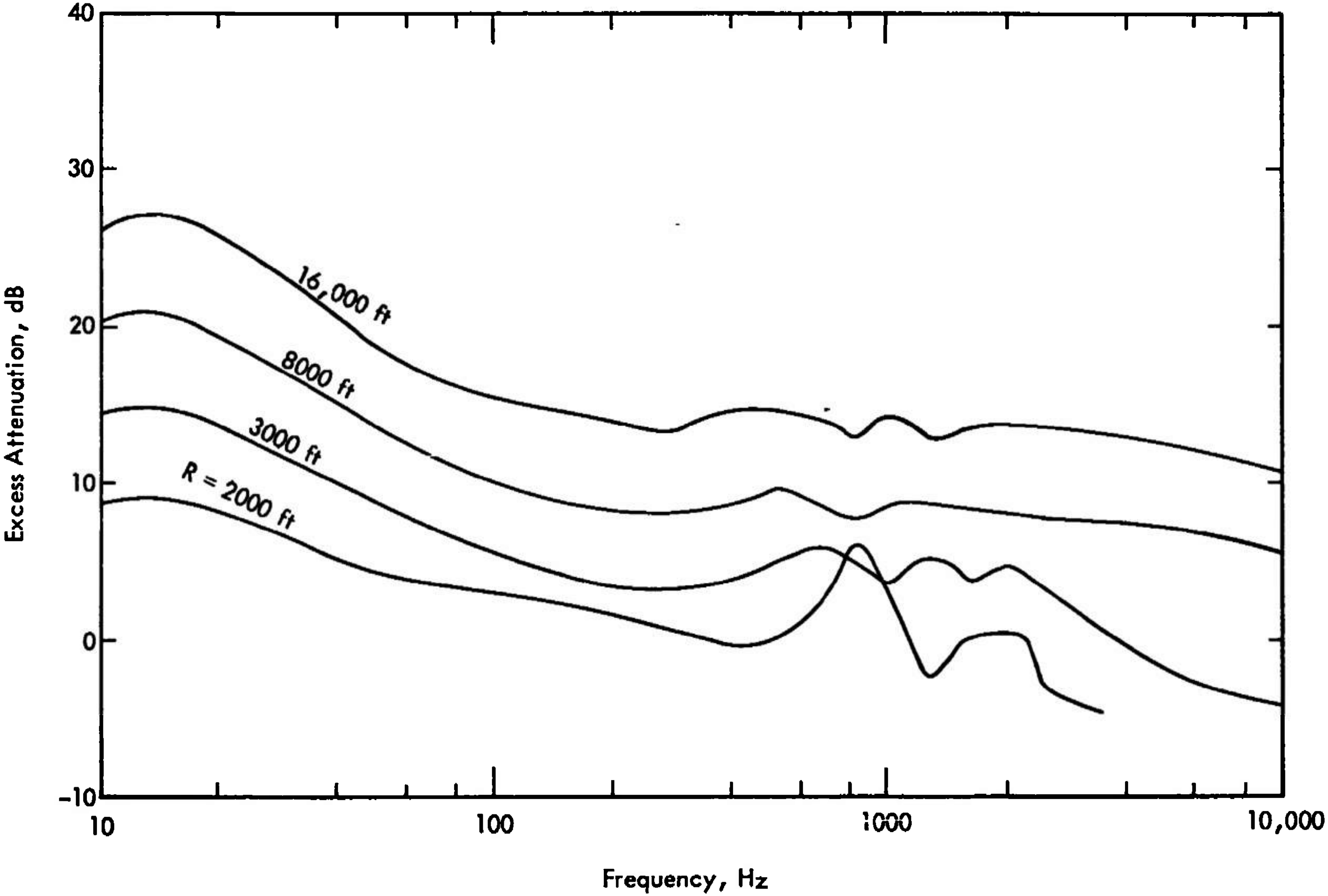

Figure B-5. Excess Attenuation Spectra for Winter Ground Cover

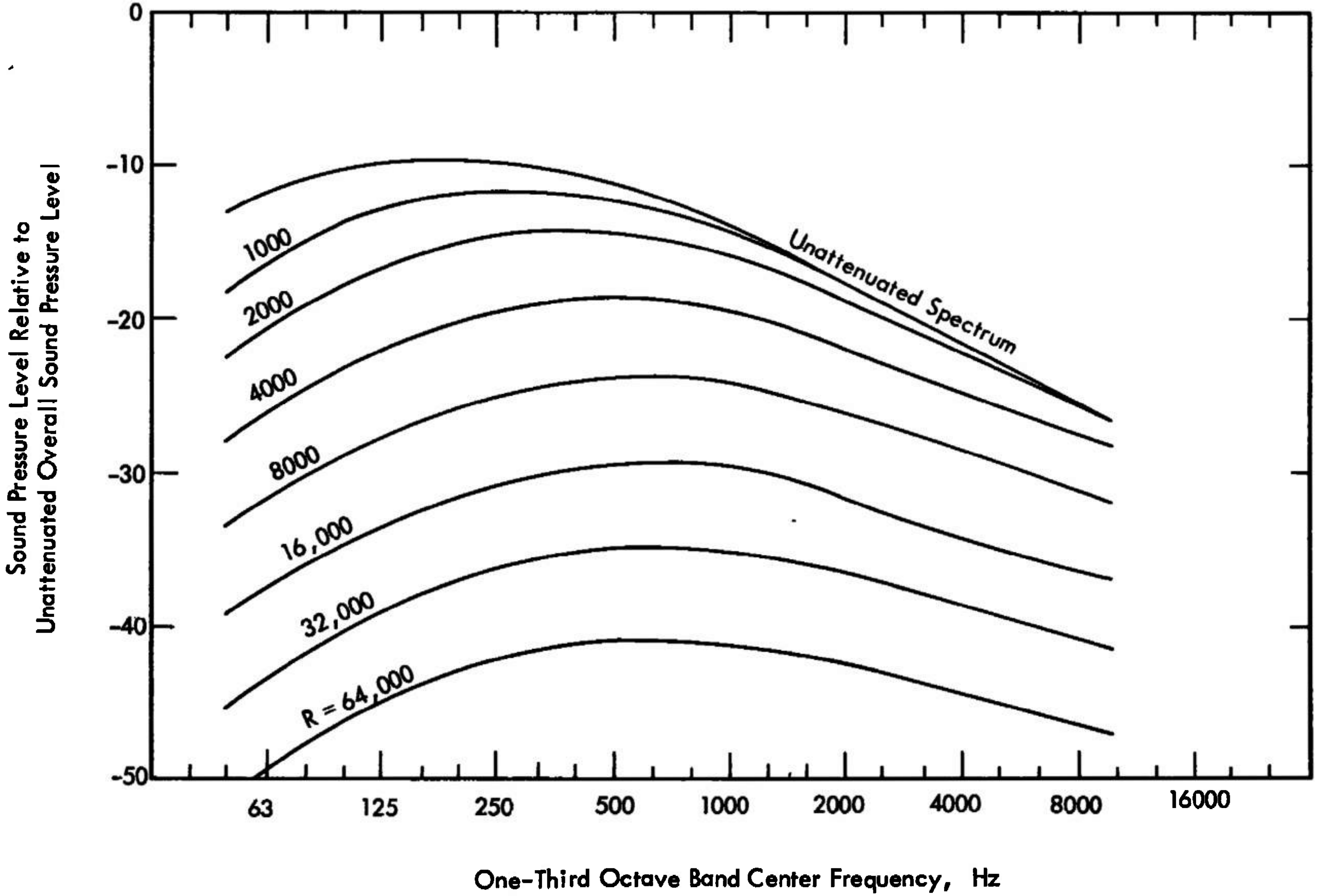

Figure B-6. Effects of Ground Attenuation on HIRT Noise Spectrum, Summer Ground Cover

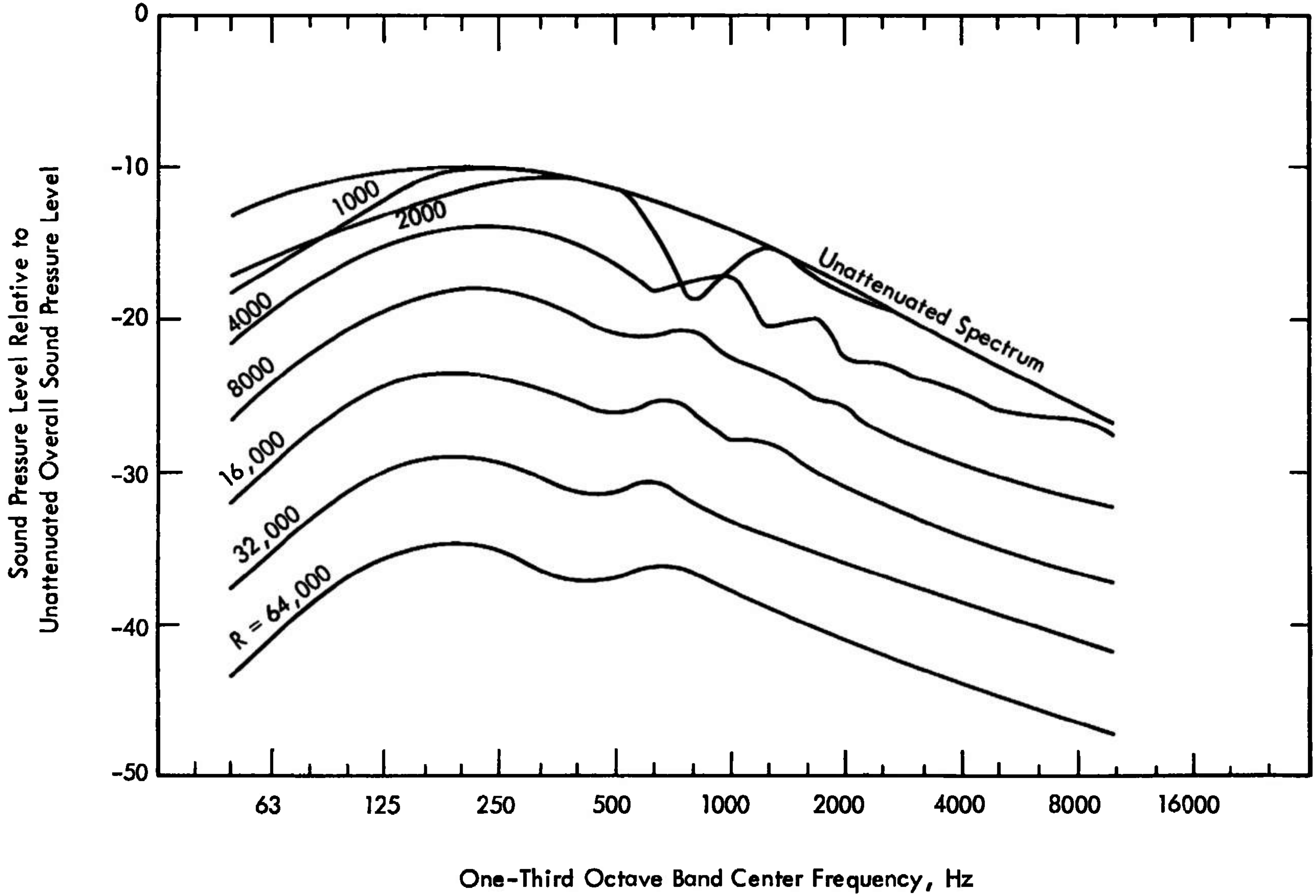

Figure B-7. Effects of Ground Attenuation on HIRT Noise Spectrum, Winter Ground Cover

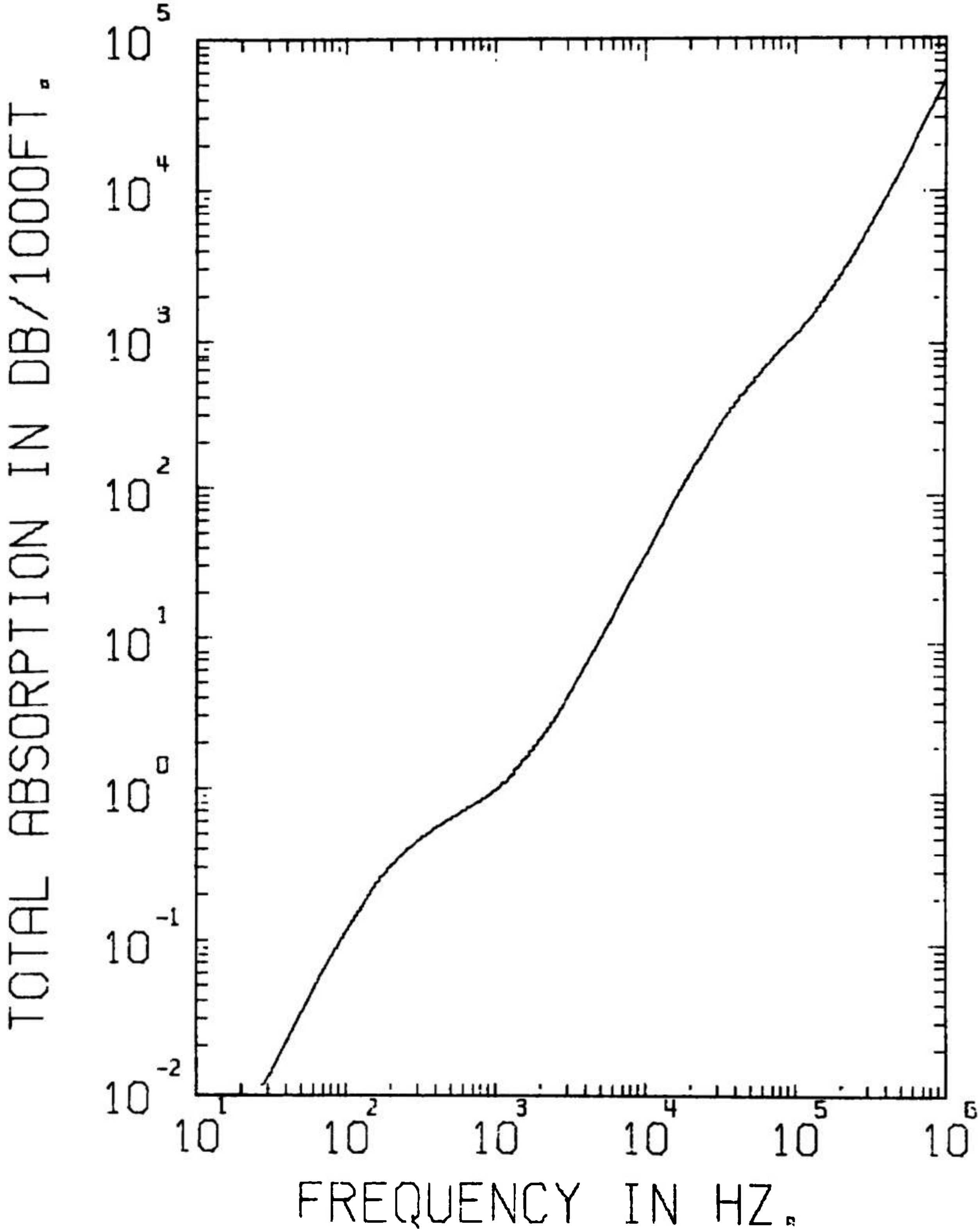

Figure B-8. Sound Absorption in Still Air for 50% Relative Humidity

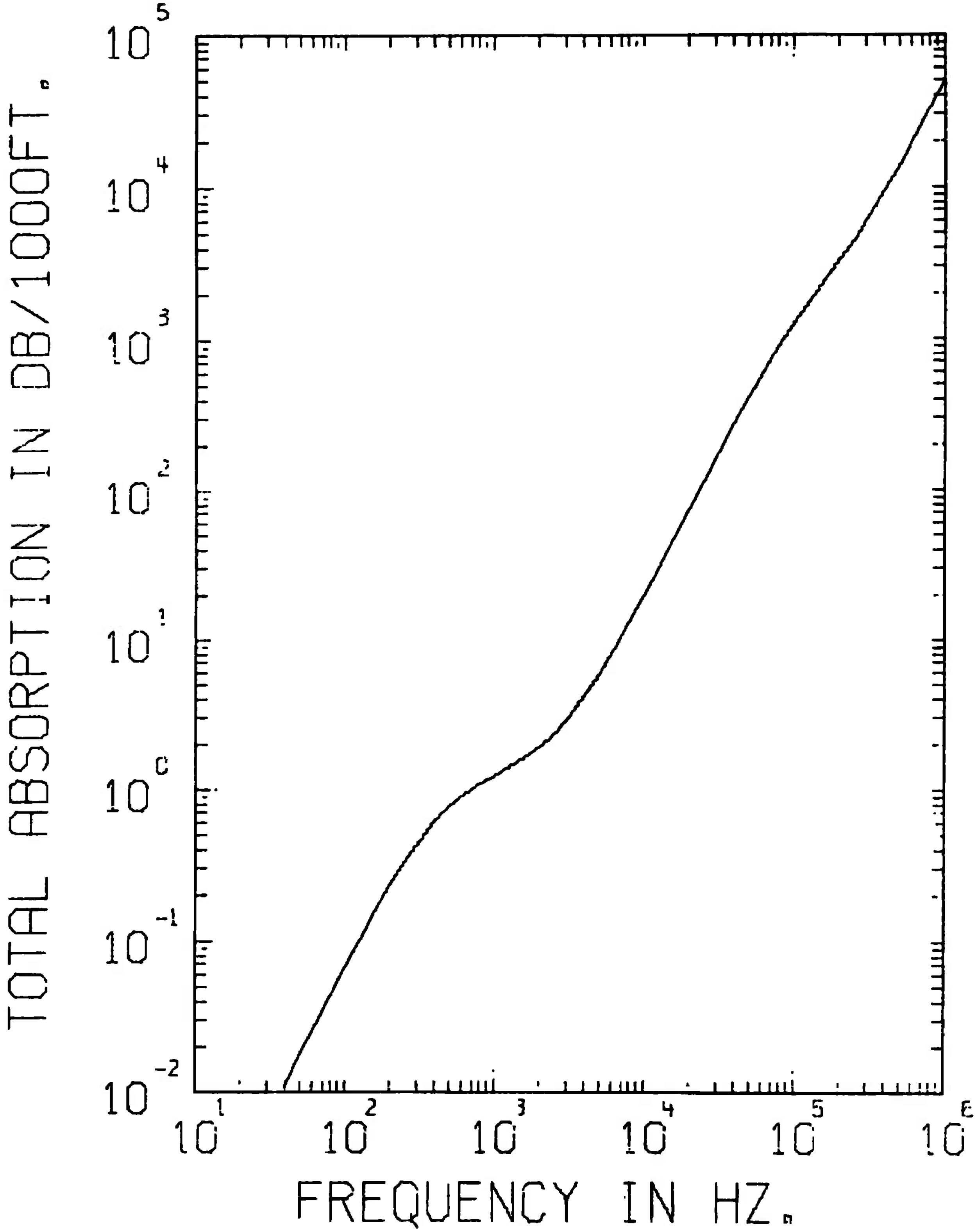

Figure B-9. Sound Absorption in Still Air for 100% Relative Humidity

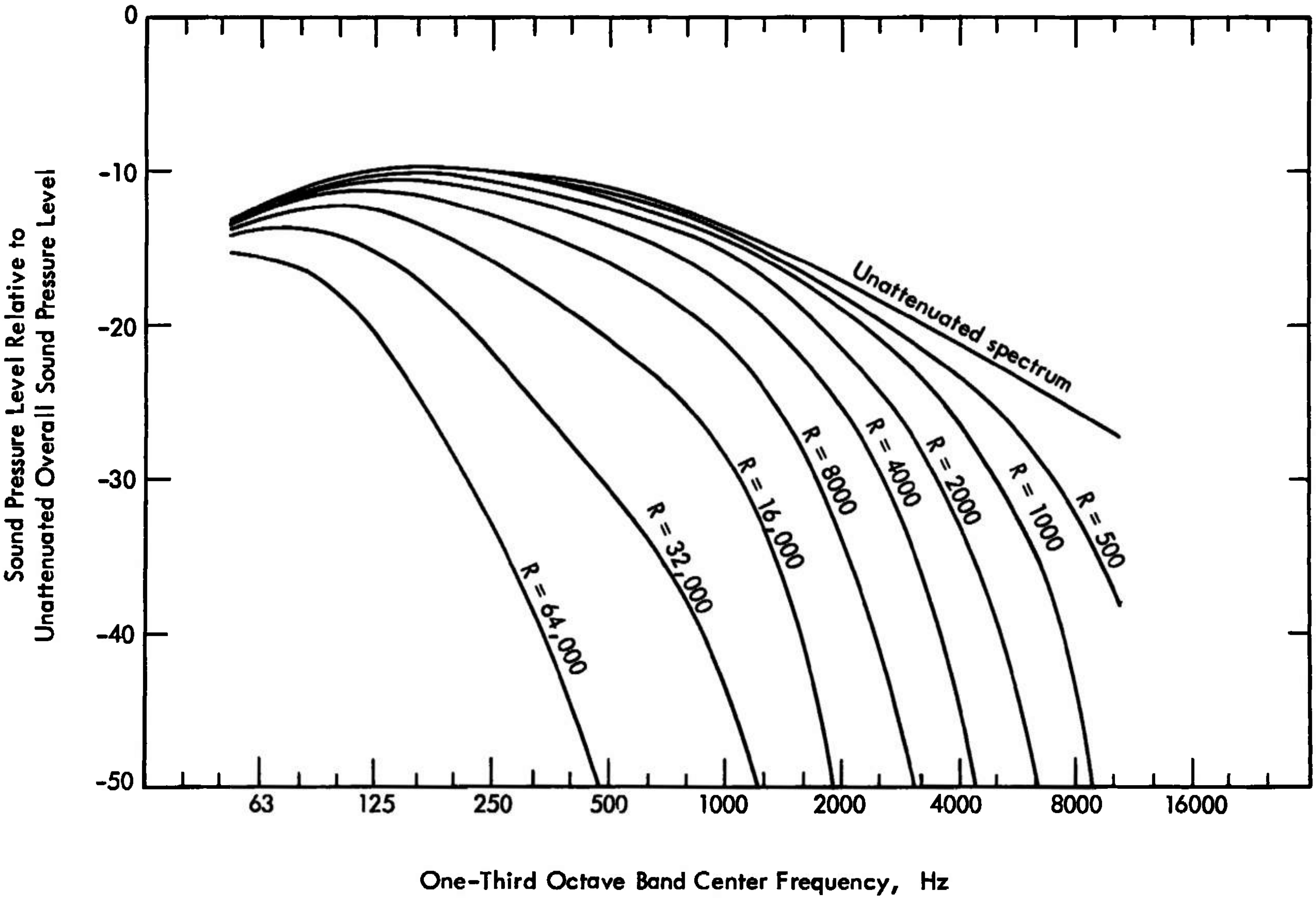

Figure B-10. Excess Attenuation of Spectrum With Distance Due to Air Absorbtion, 50% Relative Humidity

APPENDIX C

EFFECTS OF ATMOSPHERIC REFRACTION

APPENDIX C

EFFECTS OF ATMOSPHERIC REFRACTION

1.0 INTRODUCTION

Predictions of propagation effects presented in Appendix B assume that ambient sound speed is uniform, and that there are no winds. The noise environment of HIRT extends over distances of several miles. Since significant variation in the atmosphere can occur over much smaller distances, some assessment must be made of the effect of atmospheric gradients. Refraction of sound can lead to the following effects:

- Focal points, with strong amplification
- Shadow zones
- Downward refraction of sound rays unattenuated by ground cover.

In principle, acoustic ray paths could be calculated for any given atmospheric condition. In practice, such a calculation requires considerable meteorological information. This has been done in the past, for example prior to static firing of the Saturn S-1 at Marshall Space Flight Center (Reference C-1). A more critical noise problem existed in that case, as the acoustic power output was similar to HIRT but the spectrum was much lower frequency (resulting in less atmospheric absorption) and a large population center was near by. This was also a limited series of tests, so that test dates could be changed; for day-to-day HIRT operation little use could be made of detailed calculation of ray paths.

Since community reaction depends on noise exposure averaged over some time, average meteorological effects must be determined. In this section, the types of effects expected due to atmsopheric refraction will be discussed. Statistical variability of noise due to these effects, and consistent differences in noise level due to prevailing winds, must be determined by noise surveys during HIRT shake-down operations.

2.0 EFFECTS OF ATMOSPHERIC INHOMOGENEITIES

2.1 Focusing and Scattering

It is conceivable that small-scale atmospheric effects, such as thermals, large turbulent eddies, etc., might cause focuses and consequent anomalously high local noise. A considerable amount of sonic boom flight test data indicates that this is not the case. A recent review of such data may be found in Reference C-2. (The reader should be cautioned that this review seriously misinterprets theoretical studies of the mechanisms involved; it is cited here primarily for its up-to-date reference list and

and good summary of flight test data). More than 99% of measured sonic boom overpressures fall within a factor of 2 (6 dB) of predicted values. Some of this variation undoubtedly represents variation of flight parameters from nominal, so that atmospheric effects are probably less. The sound ray pattern of sonic booms is essentially cylindrical spreading; for the spherical spreading of HIRT noise, focusing effects should be less significant. Therefore, no strong focusing of HIRT noise by local atmospheric anomalies should be expected.

2.2 Refraction by a Smoothly Varying Atmosphere

For the simple calculations to follow, sound speed over altitudes are small compared to atmospheric scale height and may be taken to vary linearly with altitude:

$$a = a_1 \left(1 - \frac{y}{H} \right) \qquad \text{(C-1)}$$

where a_1 = sound speed at ground, y = altitude, and $H = -\dfrac{a}{da/dy}$. In the troposphere, the average value of H is 275,000 ft for the U.S. Standard Atmosphere 1962 (Reference C-3). For this linear, horizontally stratified model, it is straightforward to show that all ray paths are circles with centers at $y = H$. The radius and horizontal location are determined from an initial altitude and angle.

2.2.1 Shadow Zones and Diffraction

Figure C-1 is a sketch of rays from the HIRT exhaust stack in a linear atmosphere with H = 275,000 ft. No rays enter the shadow zone beyond the grazing ray. However, noise may enter this region because of diffraction. Diffraction effects at the edge of a shadow are confined to a region of width $h \approx \sqrt{\lambda r}$, where r is propagation distance and λ is wavelength (Reference C-4). Figure C-2 shows y versus r for the grazing ray, and h versus r for $\lambda = 7$ ft (corresponding approximately to the spectral peak of the exhaust flow noise). For both cases $H > y_{shadow}$ for the distances shown in the figure. Although amplitude is much diminished if distance into the shadow is a significant fraction of h, the diffraction fringe is enough larger than the shadow zone for distances of interest so that there will be no effective shadow zone under calm conditions.

2.2.2 Downward Refraction

It is possible that acceptability of HIRT noise may depend heavily on ground attenuation. Ground attenuation effects are small for rays at an angle more than 8° above the horizontal (Reference C-5). If such a ray is refracted downward, the unattenuated noise will reach the ground. This can make a considerable difference in the environmental impact. For a ray at angle θ from a source at ground level to reach the ground at location r, the sound speed scale height must be

$$H = \frac{r}{2 \tan \theta} \qquad \text{(C-2)}$$

For a source above the ground, H would be smaller. For $\theta = 8^{\circ}$ and $r = 10,000$ ft, H = 36,000 ft. This corresponds to an inversion on order of magnitude stronger than the usual gradient, and is not likely to happen.

Refraction by Wind — For the small angles involved, refraction by wind may be accounted for by adding wind speed to sound speed downwind, and subtracting it upwind. Figure C-3 shows the sound ray pattern in a wind gradient. Rays downwind are refracted downward, restricting the ground attenuation region to within some distance based on where the 8° ray meets the ground, and the shadow region upwind moves closer to the source. If the wind gradient is uniform, sound speed and wind together may be represented by Equation (C-1) (with H different upwind and downwind). The wind scale height may then be found from Equation (C-2). For the 8° ray to reach the ground at $r = 10,000$ ft requires a wind gradient of 3.1 ft/sec/100 ft, up to an altitude of about 400 ft. Wind gradients of this magnitude and larger are very possible.

3.0 CONCLUSIONS

Based on the above discussion, wecan conclude the following:

- Amplification due to strong focuses should not be expected.
- Under calm conditions, sound speed gradients are not strong enough to significantly alter the noise pattern from that predicted for a uniform atmosphere.
- Wind gradients can alter the sound ray patterns to a degree that ground attenuation may not be as great as expected. Sound levels downwind will lie somewhere between values predicted for ground cover and those predicted for clear terrain. Shadow zones may occur upwind.

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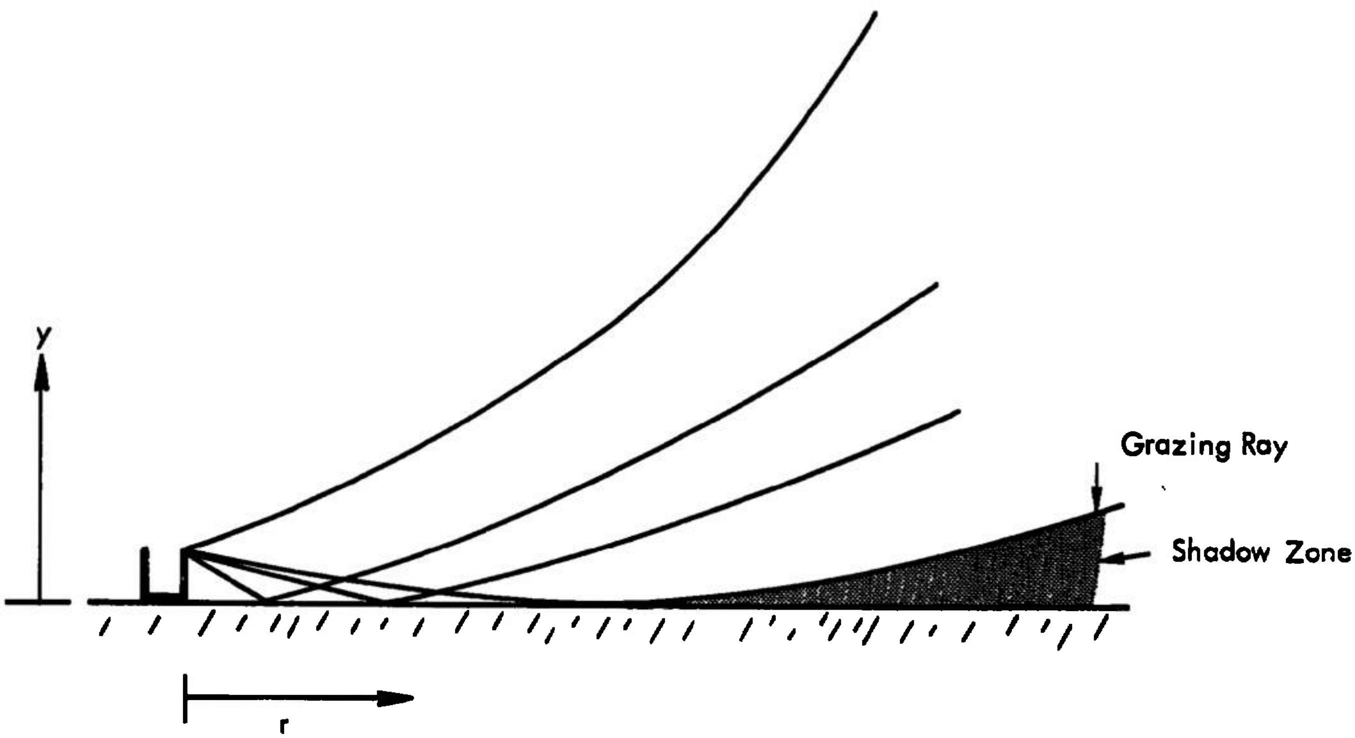

Figure C-1. Sound Ray Paths In a Real Atmosphere

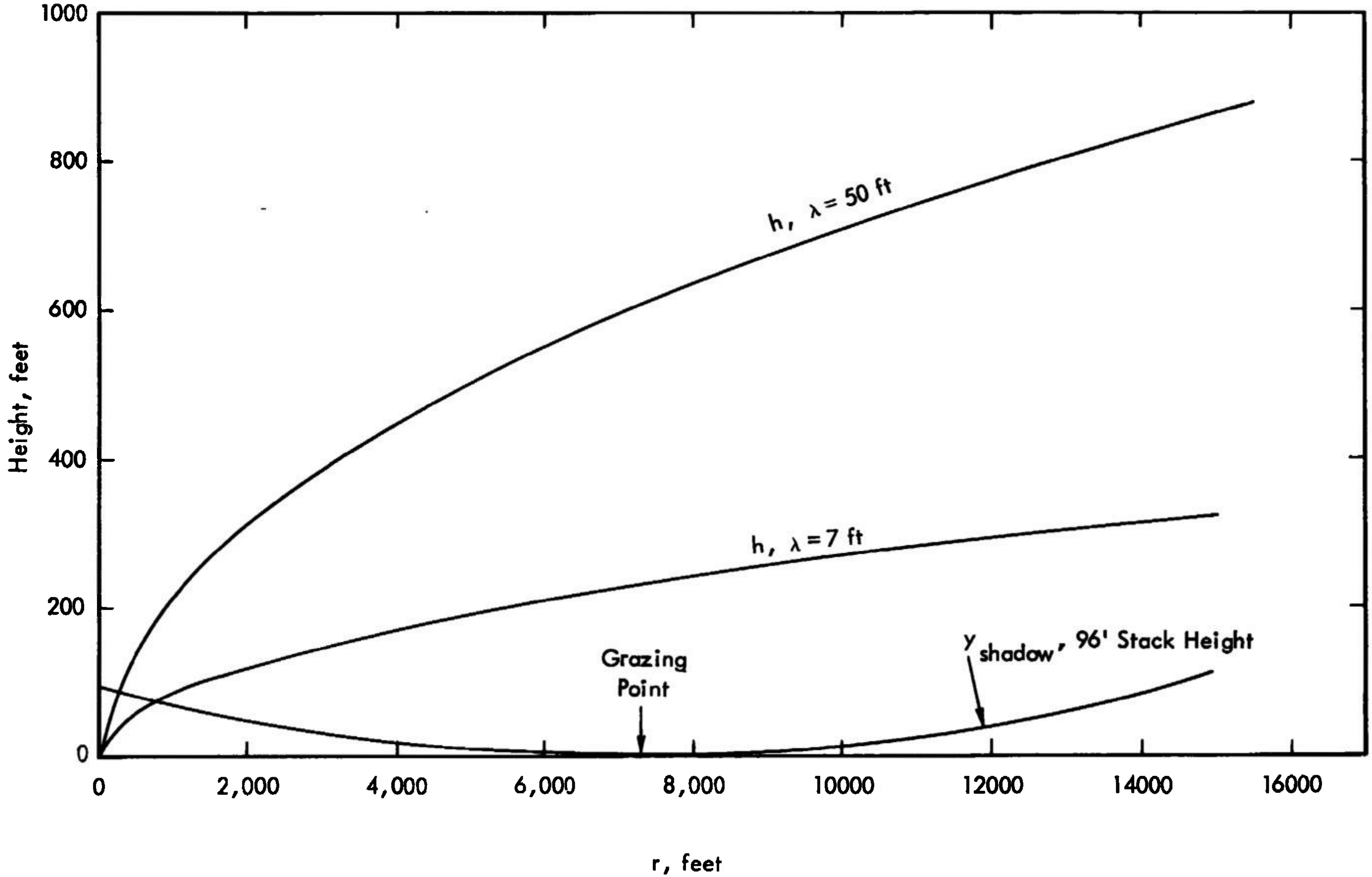

Figure C-2. Height of Shadow Zone in Standard Atmosphere, and Width of First Diffraction Fringe

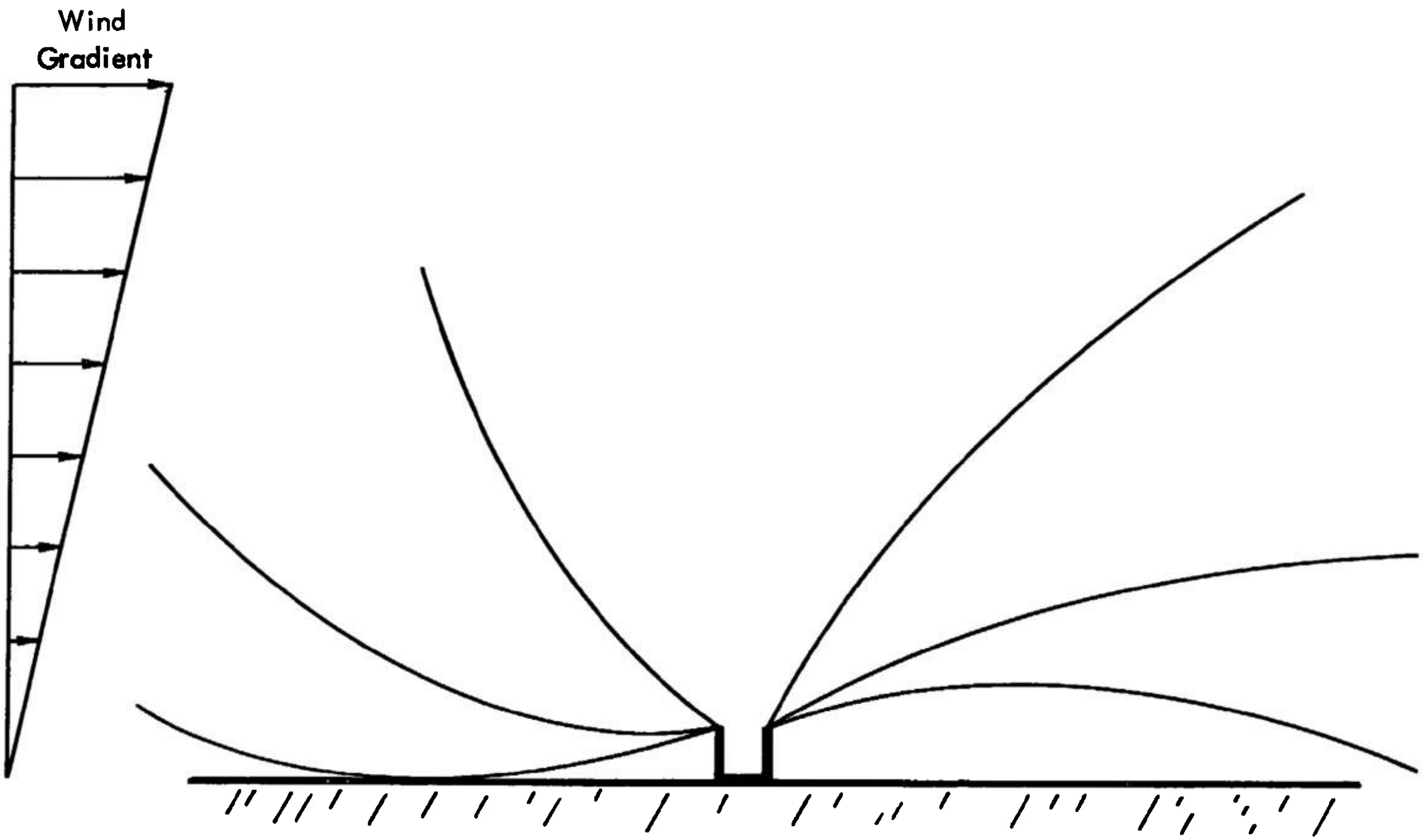

Figure C-3. Sound Ray Paths in the Presence of Wind Shear

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

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13 ABSTRACT

A study to evaluate the environmental impact of the noise produced by a proposed High Reynolds Number Tunnel (HIRT) under consideration at the Arnold Engineering Development Center (AEDC) has been conducted by Wyle Laboratories. During earlier studies, the noise characteristics of the HIRT facility were defined. These studies included 1) theoretical analyses of the noise generation mechanisms associated with the operation of the facility, and 2) scale-model experiments to provide base-line data for extrapolation to full-scale conditions. The assessment of environmental impact, based on the predicted noise environment of the full-scale facility, is the subject of this report. This assessment contains all pertinent data of relevance to the noise impact which may be anticipated during HIRT operation and includes 1) a summary of the Noise Characteristics of HIRT, 2) Specification of Acceptable Noise Limits for people, animals and buildings which will be exposed to HIRT noise, 3) the Environmental Impact of HIRT noise as evaluated by comparing HIRT noise with acceptable limit criteria, and 4) Special Considerations for Noise Protection and Control. The assessment presented herein indicates that HIRT noise will be within acceptable limits for people residing in the most heavily populated areas of surrounding communities. However, it was found that there are several areas where the anticipated noise levels are sufficiently close to permissible levels to warrant close monitoring during facility shakedown tests to assure that excessive annoyance is not imposed. These are the hospital located in Manchester, Tennessee and the Interstate Highway (I-24) which passes through the AEDC reservation. In addition, there are a few isolated rural houses near the reservation boundary which may experience noise levels slightly above recommended nighttime limits. If it is determined by facility shakedown noise monitoring that acceptable noise levels will be exceeded in these limited areas, it can be avoided by means of proper scheduling of the facility usage. On the AEDC complex, the noise levels within 3,000 feet of HIRT exceed that allowable for unprotected outdoor workers and must therefore be a controlled access area during HIRT operation. Within the developed AEDC complex, various control zones and warning systems are proposed for protection of AEDC personnel from extreme noise environments. The impact of HIRT noise on wildlife in the area is sufficiently small to be discarded as a potential problem area. No damage to AEDC buildings is anticipated; however, one large window in the model shop will be exposed to overpressures approaching that necessary to break single strength glass and therefore may require the utilization of double strength glass.*

*Subsequent to the preparation of this report, it was determined that the subject window is already equipped with double strength glass.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Reynolds number						
wind tunnels						
acoustics						
noise measurement						
noise reduction						

AFSC
Arnold AFS Tenn